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(71) Applicant:	RANDWIDTH SOLUTIONS, INC. [US/US]; 2901 Hubbard, Ann Arbor, MI 48105 (US).		
(72) Inventor:	ISLAM, Mohammed, Nazrul; 647 Spring Valley, Ann Arbor, MI 48105 (US).		
(74) Agents:	MORRIS, Francis, E. et al.; Pennie & Edmonds LLP, 1155 Avenue of the Americas, New York, NY 10036 (US).		

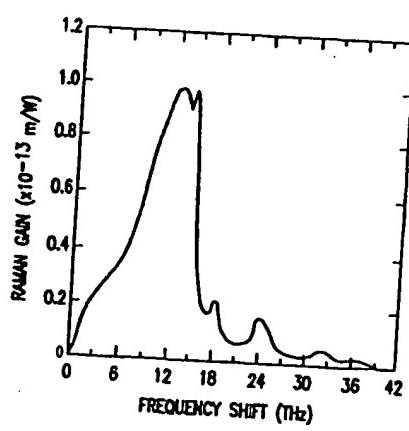
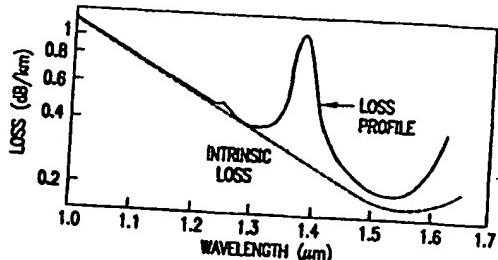
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(54) Title: BROADBAND SAGNAC RAMAN AMPLIFIERS AND CASCADE LASERS

(57) Abstract

This invention describes new developments in Sagnac Raman amplifiers (20) and cascade lasers to improve their performance. The Raman amplifier bandwidth is broadened by using a broadband pump (26, 150) or by combining a cladding-pumped fiber laser (100) with the Sagnac Raman cavity. The broader bandwidth is also obtained by eliminating the need for polarization controllers in the Sagnac cavity by using an all polarization maintaining configuration, or at least using loop mirrors (22, 24) that maintain polarization. The polarization maintaining cavities have the added benefit of being environmentally stable and appropriate for turn-key operation. The noise arising from sources such as double Rayleigh scattering is reduced by using the Sagnac cavity (22, 24) in combination with a polarization diversity pumping scheme, where the pump is split along two axes of the fiber. This also leads to gain for the signal that is independent of the signal polarization. Finally, a two-wavelength amplifier for 1310 nm and 1550 nm can be implemented by using a parallel combination of Raman amplifiers with shared pump lasers or by combining Raman amplifiers (20) with erbium-doped fiber (30) amplifiers. Combinations of the above improvements can be used advantageously to meet specifications for broad bandwidth, polarization independence, noise performance and multi-wavelength operation.



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BROADBAND SAGNAC RAMAN AMPLIFIERS AND CASCADE LASERSRELATED APPLICATION

This is a continuation-in-part application of U.S. 5 patent application serial no. 08/773,482 filed December 23, 1996, entitled "Sagnac Raman Amplifiers and Cascade Lasers," now allowed. The present application also claims the priority of U.S. provisional patent application 60/080,317 filed April 1, 1998.

10

BACKGROUND OF THE INVENTION

The present invention relates generally to Sagnac Raman amplifiers and lasers for telecommunications, cable television (CATV), and other fiber-optics applications. More 15 particularly, the invention relates to broadband Sagnac Raman amplifiers and lasers that have substantially improved bandwidth and noise performance.

20

BACKGROUND OF THE INVENTION

Because of the increase in data intensive applications, the demand for bandwidth in communications has been growing tremendously. In response, the installed capacity of telecommunication systems has been increasing by an order of magnitude every three to four years since the mid 25 1970s. Much of this capacity increase has been supplied by optical fibers that provide a four-order-of-magnitude bandwidth enhancement over twisted-pair copper wires.

To exploit further the bandwidth of optical fibers, two key technologies have been developed and used in the 30 telecommunication industry: optical amplifiers and wavelength-division multiplexing (WDM). Optical amplifiers boost the signal strength and compensate for inherent fiber loss and other splitting and insertion losses. WDM enables different wavelengths of light to carry different signals 35 parallel over the same optical fiber. Although WDM is critical in that it allows utilization of a major fraction of the fiber bandwidth, it would not be cost-effective without

optical amplifiers. In particular, a broadband optical amplifier that permits simultaneous amplification of many WDM channels is a key enabler for utilizing the full fiber bandwidth.

5 With the advent of erbium-doped fiber amplifiers (EDFAs) around 1990 to replace electronic repeaters, the capacity of telecommunication systems has since been increased by almost two orders of magnitude. Although EDFAs have had a significant impact in the past five years, they  
10 are not without problems. As shown in Figure 1a, there are two main low-loss telecommunications windows in silica-based optical fibers at wavelengths of  $1.3 \mu\text{m}$  and  $1.55 \mu\text{m}$ . EDFAs work only in the  $1.55 \mu\text{m}$  window. Yet, most of the  
15 terrestrial fibers installed in the United States during the 1970s and up through the mid 1980s are designed for operation at  $1.3 \mu\text{m}$ , and thousands of miles of  $1.3 \mu\text{m}$  terrestrial fibers have already been laid. This presents major difficulties in upgrading to the higher bandwidth EDFA technology. In the prior art, some have sought to combine  
20 EDFAs with dispersion compensators in an effort to correct the wavelength mismatch. However this approach does not permit further upgrading based on wavelength-division-multiplexing, and therefore is not seen as the best solution. Others are experimenting with new glass formulations that  
25 might provide the advantages of EDFAs at the shorter  $1.3 \mu\text{m}$  wavelength. However, currently no glass formulation has proven to be commercially viable.

Aside from the wavelength mismatch, EDFAs are also inherently prone to signal loss when the pump laser fails.  
30 EDFA is a system of the type known as a "three-level" system that does not allow the optical signal to pass through unless its pump laser is operative. Reliance on the "three-level" system could have catastrophic consequences for the reliability of fiber networks.

35 Stimulated Raman scattering amplifiers are advantageous over EDFAs because they can operate in both optical communication windows and, in fact, over the entire

transparency window of optical fibers. Moreover, the stimulated Raman scattering amplifier is a "four-level" system that simply provides no gain when its pump laser is off, but otherwise allows the optical signal to pass through the system. Stimulated Raman scattering amplifiers are based on nonlinear polarization of the dielectric silica host, and are capable of cascading to higher Raman orders or longer wavelengths. However, there is a significant problem with Raman amplifiers that has not heretofore been really overcome. Virtually every light source or pump produces some intensity fluctuation. When Raman amplifiers are allowed to cascade through several orders, the pump source intensity fluctuations are combinatorially multiplied, and very rapidly result in enormous intensity fluctuations that have made systems virtually unusable. Compounding this problem, the gain produced by this nonlinear response is proportional to instantaneous pump intensity. Thus there is no opportunity to "average out" intensity fluctuations over time. Moreover, the gain produced by Raman scattering is, itself, an exponential effect. All of these properties have lead most to conclude that stimulated Raman scattering amplifiers and cascade lasers are not suitable in general-purpose telecommunication applications.

Aside from the fluctuation problems above, several other issues also need to be addressed in order to achieve usable broadband stimulated Raman scattering amplifiers. In the prior art, a cladding-pumped fiber laser has been used as a pump source for Raman amplifiers. A commercial unit delivers 9W of single-transverse-mode output at 1100 nm with a spectral width of 4 nm. The fiber used in this laser is a rare-earth-doped, double-clad fiber. As depicted in Figure 14a, cavity mirrors are applied to the fiber ends. The mirror applied to the input end is highly reflective at the lasing wavelength of 1100 nm, while a low-reflectivity mirror or grating is applied to the output end of the fiber. The gain band for ytterbium doped fiber is roughly between 1030 nm and 1160 nm, but using a grating at the fiber end to

select one particular wavelength yields a bandwidth of about 4 nm.

While this cladding-pumped fiber laser is already quite broad in bandwidth because of multiple longitudinal modes in the cavity, it would be desirous to further broaden the pump wavelength range to achieve broadband Raman gain. The broader pump bandwidth is also advantageous to avoid reflections associated with stimulated Brillouin scattering in the gain fiber of the Raman amplifier.

10 Polarization controllers (PCs) are used in almost all Raman amplifiers to regulate polarization states. A fiber based PC is typically constructed using quarter-wave loops of optical single-mode fiber mounted in such a way as to allow precise rotation of the loops about a common 15 tangential axis. Each loop is designed to function as a quarter-wave retarder for the wavelength range of interest. By rotating a loop about its tangential axis, the loop's birefringence is rotated. Combining three or four loops in series increases the wavelength range and adjustment range of 20 the controller and enables complete and continuous polarization adjustability. However, as the temperature changes, the fiber birefringence changes and the mechanical setting of the PCs may also be perturbed. As a result, the PCs may ruin the "turn-key" operation of the amplifier 25 because they could require periodic readjustment with changing environmental conditions.

In the past attempts at applying Raman amplifiers to analog signal amplification, it was discovered that a major limitation arises from the noise associated with Double 30 Rayleigh Scattering (DRS). Stimulated Rayleigh scattering refers to light scattering due to induced density variations of a material system. More specifically, stimulated Rayleigh refers to the scattering of light from isobaric density fluctuations.

35 Stimulated Rayleigh scattering gives rise to a backward traveling wave that is at the same center frequency as the signal input, somewhat broadened by the Rayleigh

linewidth (defined as a reciprocal to characteristic decay time of the isobaric density disturbances that give rise to Rayleigh scattering). For example, J.L. Gimlett, et al., *IEEE Photonics Technology Letters*, Vol. 2, p.211 (March 1990) disclosed that the Rayleigh scattering can be modeled as a Rayleigh mirror with a prescribed reflectivity. DRS refers to a second stimulated Rayleigh scattering event that scatters the backward traveling wave back into the original signal, thereby leading to interference with the original signal, cross-talk, and increased uncertainty of the amplitude (i.e., noise). Also, the DRS is proportional to the pump intensity, the signal intensity, and the length of the gain fiber. Therefore, the DRS noise source is a direct consequence of requiring high pump powers and long interaction lengths due to the inefficiency of the Raman amplification process.

Prior art has shown that insertion of an optical isolator midway through the amplifier and the use of two WDMs to guide the pump radiation around the isolator can reduce the DRS effect. In effect, the amplifier is split into two parts and the net gain is accumulated through both sections, but the isolator reduces the DRS in half. Although this technique has been used for high gain EDFA's and in ring designs of Raman amplifiers, it increases the complexity and cost of the amplifier considerably due to the need for two additional WDMs and one isolator.

As shown from the attenuation curve for fibers in Figure 1a, there are two low-loss windows for telecommunications. In the prior art, EDFA technology has been developed to make full use of the  $1.5 \mu\text{m}$  window. Since Raman amplification can be obtained over the entire transparency range for optical fibers, Raman amplification can be applied to both the  $1.3 \mu\text{m}$  and  $1.5 \mu\text{m}$  windows. Because future communication applications will demand the broadest bandwidth available over the existing fiber base, to fully utilize optical fiber's bandwidth, it is desirable to

have an amplifier which will use both telecommunications windows and operate with WDM simultaneously.

#### SUMMARY OF THE INVENTION

5 It is an object of the present invention to provide a Sagnac Raman amplifier and cascade laser which is operable in both 1.3  $\mu\text{m}$  and 1.5  $\mu\text{m}$  windows.

10 It is another object of the present invention to provide a broadband Sagnac Raman amplifier and cascade laser which is operable in both 1.3  $\mu\text{m}$  and 1.5  $\mu\text{m}$  windows.

15 It is another object of the present invention to provide a broadband pump for use in a broadband Sagnac Raman amplifier and cascade laser.

It is another object of the present invention to  
20 remove environment-sensitive elements from the cavity of the Sagnac Raman amplifier and cascade laser.

It is another object of the present invention to provide a polarization independent Sagnac Raman amplifier and cascade laser.

25 20 It is another object of the present invention to improve noise performance of the Sagnac Raman amplifier and cascade laser.

It is yet another object of the present invention to provide a parallel optical amplification apparatus having  
25 a combination of the Sagnac Raman amplifier and EDFA for the 1.3  $\mu\text{m}$  and 1.5  $\mu\text{m}$  low-loss windows of optical fibers.

The present invention attacks the intensity fluctuation problem with Raman amplifiers by recognizing that higher order intensity fluctuations are a distributed effect  
30 (everywhere present in the distributed gain medium that produces the optical signal gain) that can be significantly reduced by a reflector structure that rejects intensity fluctuations originating in this distributed effect. The present invention employs a reflector structure that defines  
35 two optical paths within the distributed gain medium, configured to support both common mode and difference mode optical signals. By choosing a configuration that propagates

higher order intensity fluctuations in the difference mode, much of the unwanted amplification of pump fluctuations is rejected.

Although numerous configurations are possible, one embodiment employs a Sagnac interferometer as one of the two optical resonator reflectors. The Sagnac interferometer employs an optical coupler with both ends of a fiber loop (a distributed gain medium) connected to its light splitting ports. The coupler thus establishes two optical paths, a clockwise path and a counterclockwise path. Signals are compared at this optical coupler, with common mode signals being substantially reflected and difference mode signals being at least partially rejected through a rejection port associated with the optical coupler. Although intensity fluctuations originating at the pump (at the pump wavelength) are amplified, any intensity fluctuations resulting from higher order stimulation of the distributed gain medium are at least partially rejected as difference mode signals.

This specification describes inventions leading to a broadband Raman amplification that would be compatible with WDM technologies. Four improvements over the original Sagnac Raman amplifier and laser are discussed.

First, broad bandwidth is achieved by using a broadband laser or amplifier cavity combined with a broadband pump. The broadband pump has a pump laser and a bandwidth adding mirror connected thereto to generate a broadened pump spectrum. The bandwidth adding mirror can be a Sagnac loop mirror with an unequal ratio coupler. It further has a phase/amplitude modulator asymmetrically located within the Sagnac loop mirror. The pump laser is a cladding pumped fiber laser. In one preferred embodiment, the broadband pump is incorporated directly into the laser or amplifier cavity.

Second, turn-key operation is obtained by minimizing the need for polarization controllers through use of a polarization maintaining cavity. In one embodiment, the Sagnac loop mirror of the broadband Sagnac Raman amplifier is fabricated from polarization maintaining fiber cross-spliced

at the middle of the loop mirror. In another embodiment, the Sagnac loop mirror is made of polarization maintaining fiber and the Raman gain fiber is separated from the Sagnac loop mirror. Input and output ports of the amplifier are 5 polarization maintaining WDMs.

Third, the noise performance is improved and protection against double Rayleigh scattering is provided by using a polarization diversity pumping system. In one embodiment of the polarization diversity pumping system, the 10 pumping light is launched at a 45 degree angle into the polarization maintaining fiber to produce a beam having two polarization directions. Such angle is achieved by either rotating the fiber or using a quarter wavelength plate. In another embodiment, the pumping light is first divided by a 15 50:50 coupler into two beams. One beam travels through a retarder to change its polarization direction. Then a polarization beam splitter combines the two beams. In yet another embodiment, the polarization maintaining fiber is spliced at a 45 degree angle to the cladding-pumped fiber to 20 output a beam having two polarization directions.

Finally, two-wavelength operation is achieved between two parallel amplifiers for two separate windows. In one embodiment, both 1310 nm and 1550 nm amplifications are performed by the broadband Sagnac Raman amplifiers. 25 Moreover, the two amplifiers share a common pump laser. In another embodiment, a combination of Raman amplifiers and EDFA's are used. The Sagnac Raman amplifier is used to amplify the 1310 nm signal, while the 1550 nm signal is amplified by the EDFA. The EDFA may be pumped by another 30 Sagnac Raman cascade laser.

For a more complete understanding of the invention, its objects and advantages, reference may be had to the following specification and to the accompanying drawings.

35

#### BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1a is a graph of the loss or attenuation in typical single-mode optical fibers. The solid curve is a

measured loss profile, and the dashed curve shows the intrinsic loss profile resulting from Rayleigh scattering and absorption in pure silica.

Figure 1b is a graph depicting Raman gain as a function of frequency shift for fused silica at a pump wavelength of 1  $\mu\text{m}$ ;

Figure 2 is a diagrammatic illustration of a first embodiment of a Sagnac Raman amplifier in accordance with the present invention.

Figures 3a and 3b are illustrations that accompany the equations used to generate values presented in Table I.

Figure 4 is a diagrammatic illustration of a second embodiment of a Sagnac Raman amplifier of the present invention employing dichroic couplers for wavelength discrimination.

Figure 5 is a diagrammatic illustration of a third embodiment of a Sagnac Raman amplifier of the present invention employing one or more grating reflectors.

Figure 6 is a diagrammatic illustration of a fourth embodiment of a Sagnac Raman amplifier of the present invention employing an uneven coupler.

Figure 7a is a diagrammatic illustration of a fifth embodiment of a Sagnac Raman amplifier of the present invention employing a Fabry-Perot filter;

Figure 7b depicts in detail the Fabry-Perot filter employed in the embodiment of Figure 7a.

Figure 8 is a diagrammatic illustration of a first embodiment of the Sagnac Raman cascade laser of the invention.

Figure 9 is a diagrammatic illustration of a second embodiment of the Sagnac Raman cascade laser of the invention providing bidirectional output with a single coupler.

Figure 10 is a diagrammatic illustration of a third embodiment of the Sagnac Raman cascade laser of the invention employing a dichroic coupler.

Figure 11 is a diagrammatic illustration of a fourth embodiment of the Sagnac Raman cascade laser of the invention employing a dichroic mirror at the cavity end.

5 Figure 12 illustrates the general principle of using a bandwidth adding mirror to a pump laser to broaden the bandwidth of the pump laser.

Figure 13 depicts the spectral broadenings possible due to the nonlinearity in optical fibers.

10 Figure 14a depicts a prior art pump configuration where the wavelength of the pump laser is selected by placing a grating at the fiber output at the desired wavelength.

Figure 14b is a diagrammatic illustration of a first embodiment of the broadband pump of the invention employing a Sagnac loop as the cavity end mirror.

15 Figure 14c is a diagrammatic illustration of a second embodiment of the broadband pump of the invention modulating either the Sagnac loop or the drive to the cladding-pumped fiber laser.

20 Figure 15a is a diagrammatic illustration of a first embodiment of a broadband Sagnac Raman amplifier where the amplifier spectrum is broadened by using a broadened pump laser such as one of those of Figures 14b and 14c.

Figure 15b is a diagrammatic illustration of a second embodiment of the broadband Sagnac Raman amplifier.

25 Figure 16a is a diagrammatic illustration of a preferred embodiment of the broadband Sagnac Raman cascade laser combining the broadband pump with the Sagnac Raman cascade laser.

30 Figure 16b is a diagrammatic illustration of a preferred embodiment of the broadband Sagnac Raman amplifier combining the broadband pump with the Sagnac Raman amplifier.

Figure 17 is a diagrammatic illustration of the broadband Raman amplifier with a gain flattening element at the output.

35 Figure 18a is a diagrammatic illustration of one embodiment of a Sagnac Raman amplifier using an all-polarization-maintaining cavity.

Figure 18b illustrates an alternate embodiment of Figure 18a using a bulk 50:50 beam splitter instead of the PM coupler.

Figures 19a is a diagrammatic illustration of an 5 embodiment in which a Sagnac loop mirror made of a short length PM fiber is used.

Figures 19b is a diagrammatic illustration of an embodiment in which two Sagnac loop mirrors made of a short length PM fiber are used.

10 Figure 20a is a diagrammatic illustration of a first embodiment for polarization diversity pumping of the Raman amplifier or laser in with the use of a length of polarization maintaining fiber.

15 Figure 20b is a diagrammatic illustration of a second embodiment for polarization diversity pumping of the Raman amplifier or laser with the use of two optical paths.

Figure 21 illustrates one embodiment of the combined pump laser and Sagnac Raman amplifier cavity for polarization diversity pumping.

20 Figure 22a is a diagrammatic illustration of a parallel combination of Sagnac Raman amplifiers for amplifying both wavelengths while using a common pump laser.

25 Figure 22b is a diagrammatic illustration of one Sagnac Raman amplifier for 1310 nm, and another Sagnac Raman laser operating at 1480 nm for pumping of an EDFA at 1550 nm. Both the Sagnac amplifier and laser share a common pump laser.

30 Figure 22c illustrates the use of a Sagnac Raman amplifier for 1310 nm in parallel with an EDFA for 1550 nm amplification.

#### DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention provides a structure that 35 combines Sagnac interferometer technology with Raman amplifier technology to achieve performance improvements that neither technology, by itself, has heretofore been able to

deliver. More specifically, the preferred embodiments relates to broadband Sagnac Raman amplifiers and lasers that have substantially improved bandwidth and noise performance. To provide a better understanding of the amplification mechanism at work in the present invention, some knowledge of the Raman effect will be helpful.

### 1. Stimulated Raman Scattering

Stimulated Raman scattering is an important nonlinear process that can turn optical fibers into amplifiers and tunable lasers. Raman gain results from the interaction of intense light with optical phonons in the glass, and the Raman effect leads to a transfer of energy from one optical beam (the pump) to another optical beam (the signal). An interesting property of Raman gain is that the signal is downshifted in frequency (upshifted in wavelength) by an amount determined by the vibrational modes of the glass. Figure 1b depicts the Raman gain coefficient  $g_r$  for silica fibers. Notably, the gain  $g_r$  extends over a large frequency range (up to 40 terahertz [THz]), with a broad peak centered at 13.2 THz (corresponding to a wavelength of 440 cm<sup>-1</sup>). This broad behavior is due to the amorphous nature of the silica glass and means that the Raman effect can be used to make broadband amplifiers. The Raman gain depends on the composition of the fiber core and can vary with different dopant concentrations.

The present invention employs a distributed gain medium comprising a material that produces optical signal gain due to third order nonlinearities in the material, in which the gain is proportional to the intensity of the light passing through the medium. By way of background, the response of any dielectric to light becomes nonlinear for intense electromagnetic fields, and optical fibers are no exception. This nonlinear response is related to anharmonic motion of bound electrons under the influence of an applied field. The induced polarization  $P$  from the electric dipoles

is not linear in the electric field E. Rather, it satisfies the more general relationship described in equation (1)

$$P = \epsilon_0 [\chi^{(1)} \cdot E + \chi^{(2)} : EE + \chi^{(3)} : EEE \dots] \quad (1)$$

5

where  $\epsilon_0$  is the vacuum permittivity and  $\chi^0$  ( $j = 1, 2, \dots$ ) is the jth order susceptibility. To account for the light polarization effects,  $\chi^0$  is a tensor of rank  $j + 1$ . The linear susceptibility  $\chi^{(1)}$  represents the dominant contribution to P. Its effects are included through the refractive index n and the attenuation coefficient a. The second order susceptibility  $\chi^{(2)}$  is responsible for such nonlinear effects as second harmonic generation and sum-frequency generation. However, this second order susceptibility is nonzero only for media that lack an inversion symmetry at the molecular level. Since silicon dioxide is a symmetric molecule,  $\chi^{(2)}$  vanishes for silica glasses. As a result, optical fibers do not normally exhibit second order nonlinear effects. Nevertheless, dopants introduced inside the fiber core can contribute to second harmonic generation under certain conditions.

The third order susceptibility  $\chi^{(3)}$ , which is responsible for phenomena such as third harmonic generation, four-wave mixing and nonlinear refraction, is present in optical fibers. It is this third order nonlinearity that is operative in the present invention. These third order nonlinear effects are identifiable as being variable in proportion to the intensity of the light.

From a functional standpoint, stimulated Raman scattering amplifiers can be pumped at any wavelength because there is no pump absorption band, while the signal gain characteristics are determined by the optical phonon spectra. This means that stimulated Raman scattering amplifiers are capable of cascading to higher Raman orders or longer

wavelengths. Cascading is the mechanism by which optical energy at the pump wavelength is transferred, through a series of nonlinear polarizations, to an optical signal at the longer signal wavelength. Each nonlinear polarization of 5 the dielectric produces a molecular vibrational state corresponding to a wavelength that is offset from the wavelength of the light that produced the stimulation. The nonlinear polarization effect is distributed throughout the dielectric, resulting in a cascading series of wavelength 10 shifts as energy at one wavelength excites a vibrational mode that produces light at a longer wavelength. This process can cascade through numerous orders. The ability to cascade makes stimulated Raman scattering amplifiers very attractive, for it allows operation over a wide range of different 15 wavelengths.

Hence, Raman amplification has a number of attractive features. First, Raman gain exists in every fiber; Raman gain is a good candidate for upgrading existing fiber optic links. Second, unlike EDFA's, there is no 20 excessive loss in the absence of pump power, an important consideration for system reliability. Third, the gain spectrum is very broad (bandwidth of greater than 5 THz around the peak at 13.2 THz), so that it can be used to amplify multiple wavelengths (as in wavelength division 25 multiplexing) or short optical pulses. Also, Raman amplification can be used for distributed amplification, which may be especially valuable for ultra-high-bit-rate systems. Finally, by varying the pump wavelength or by using cascaded orders of Raman gain, the gain can be provided over 30 the entire telecommunications window between 1.3  $\mu\text{m}$  and 1.6  $\mu\text{m}$ .

## 2. Embodiments of Sagnac Raman Amplifiers

Figure 2 illustrates a first embodiment of the 35 Sagnac Raman amplifier 20 that comprises at least two reflectors 22, 24 and a port 28 for coupling to a source of light. Specifically, reflector 22 may be any reflective

structure such as a mirror. Reflector 24 is a loop reflector such as a Sagnac interferometer. In this embodiment, these two reflectors form therebetween an optical resonator. The light source 26 is a pumped fiber laser coupled through a WDM 5 port 28 to the optical resonator. An optical signal is injected into the optical resonator and this signal is then amplified by the optical energy introduced by the light source 26. An optical signal input WDM port 42 is provided to allow the optical resonator to be used as an optical 10 amplifier. The optical signal then exits from an optical signal output WDM port 44.

The light source 26 can be any suitable source of optical energy. Because the Raman effect relies upon intense optical energy, high power semiconductor or cladding-pumped 15 fiber lasers are presently preferred. A suitable high power source is available from Spectra Diode Lasers, Inc., San Jose, California. The wavelength of the optical energy from light source 26 will, of course, be chosen to match the desired application. By way of example, in an embodiment 20 designed for 1.3  $\mu\text{m}$  telecommunication applications, the light source 26 provides light at a wavelength of 1117 nm. This light is introduced through the wavelength division multiplexing (WDM) coupler 28. The optical signal to be amplified, injected through WDM coupler 42, may be at a 25 wavelength of 1300 nm to 1310 nm. The injected signal propagates in the clockwise direction around loop 30 and is then removed using WDM coupler 44. Due to the frequency downshift (wavelength upshift) of the Raman effect, the wavelength of the light source 26 is upshifted to match that 30 of the signal. Although a 1.3  $\mu\text{m}$  amplifier example is presented here, the configuration illustrated in Figure 2 and the embodiments described elsewhere in this specification can be configured to work at other wavelengths as well. Thus the light source 26 can be any suitable wavelength to match the 35 application (not necessarily at 1117 nm) and the two WDM couplers 42 and 44 can be designed for any desired signal wavelengths (not necessarily between 1300 nm and 1310 nm).

The resonant cavity of the embodiment illustrated in Figure 2 lies between reflector 22 and reflector 24. In the illustrated embodiment the optical fiber disposed between these two reflectors serves as the light transmissive medium.

5 The Sagnac reflector 24 is fabricated using a distributed gain medium comprising a material that produces optical signal gain through third order nonlinearities in the material, characterized by a gain that is proportional to the intensity of the light passing through the medium. Although 10 reflector 22 is shown as a discrete mirror in the embodiment, it will be appreciated that reflector 22 could be any form of reflector, including a simple metallic coating evaporated onto the fiber end. Thus the invention can be implemented as an all fiber configuration. Some of the embodiments yet to 15 be described use other forms of reflectors for reflector 22.

The Sagnac interferometer that serves as reflector 24 is fabricated from a length of optical fiber that may be suitably coiled to accommodate the physical packaging requirements. The Sagnac interferometer comprises a fiber 20 loop 30, typically a kilometer or more in length. The fiber loop is established using a coupler such as 50:50 coupler 32. The 50:50 coupler defines two signal paths, such that half of the light from light source 26 travels around loop 30 in a clockwise direction and half of the light from light source 25 26 travels around loop 30 in a counterclockwise direction. These two optical paths support both common mode and difference mode optical signals. To illustrate, assume that a continuous wave burst of light is injected via WDM 28 from light source 26. The CW burst enters the Sagnac 30 reflector 24; half of the energy propagates in a clockwise direction and half of the energy propagates in a counterclockwise direction. After propagating through the Sagnac reflector, the continuous wave burst is then reflected back in the direction of WDM 28, where the burst then 35 reflects from reflector 22 and is again transmitted to the Sagnac reflector, where the cycle repeats. The CW burst thus resonates between the two reflectors 22 and 24, growing in

energy at the resonant frequency. This is the common mode signal path. The system is designed to reflect the common mode signal between reflectors 22 and 24, whereby the optical amplification occurs.

5 Now consider a noise burst signal that originates at some random location along fiber loop 30. For purposes of the illustration, assume that the noise burst is injected at a location designated by N in Figure 2. Some of the energy of the noise burst (that which propagates in the clockwise direction) passes out through rejection port 46 where it is not returned to the system. The remainder (propagating in the counterclockwise direction) is reflected within the system and therefore retained. Because the signal paths of the noise burst are unbalanced (difference mode), a portion 10 of the noise burst energy (approximately half of the energy) is lost, thus lowering the noise level within the system. The noise burst originating in the fiber loop travels in a difference mode, in which one optical path is retained within the system and the other optical path is discharged through 15 rejection port 46. This is how the invention is able to reduce higher order amplification of pump source fluctuation. The higher orders originate (through the Raman effect) within the fiber loop and are thus treated as difference mode signals.

20 25 One advantage of using the Sagnac reflector 24 is its inherent broadband properties. Unlike some other systems that are restricted by the laws of physics to operate at a single resonant frequency dictated by doping, the present invention operates over a broad range of frequencies, the operating frequency being dependent principally upon the frequency of the input signal. Of course, if desired, frequency-selective gratings or frequency-selective filters can be employed within the laser cavity if precise wavelength control is desired.

30 35 One significant advantage of the invention results from the union of the Sagnac loop mirror with the Raman amplifier technology. Conventionally, a large source of

amplitude jitter in Raman lasers arises from the pump fluctuations that become greatly amplified in the highly nonlinear cascaded Raman process. Advantageously, the Sagnac loop mirror results in a quieter amplifier (and also a 5 quieter laser) due to its difference mode noise rejection properties. The Sagnac loop tends to dampen noise at frequencies larger than the inverse round-trip time of the loop cavity. For example, for a 2 kilometer (km) long fiber loop, noise at frequencies larger than 100 kilohertz (kHz) 10 will be partially rejected via the rejection port 46. Also, spurious signals and noise injected at some arbitrary point along the loop are also attenuated.

As previously noted, the Raman amplifier is capable of cascading through multiple orders. With each cascade 15 order there is a corresponding shift in optical wavelength. The wavelength shift corresponds to a predetermined Stokes wavelength. Thus to achieve a 1310 nm signal wavelength four cascaded orders of Stokes shift would be employed, namely: 1117 nm to 1175 nm to 1240 nm to 1310 nm. Similarly, a fifth 20 Stokes shift, based on the previous cascaded orders, would produce an output wavelength at 1480 nm.

Cascading is a desirable property; it allows the system designer to shift the pump wavelength to any number of different desired signal wavelengths. Thus commercially 25 available, high-powered pumps can be wavelength shifted to match the wavelength of the signal being amplified. However, cascading comes at a price. Pump fluctuations are amplified combinatorially, as the examples of Table I demonstrate. Table I shows how a 10% intensity fluctuation at the pump 30 cascades exponentially with each cascaded order. Table I compares two cases. Case 1 assumes a 10% fluctuation introduced in the first step, using a simple Fabry-Perot (linear) cavity so that there is no rejection of the fluctuation burst. Case 2 assumes a 10% fluctuation 35 introduced in the second step, using a Sagnac Raman laser cavity with a 50% rejection of the fluctuation burst. Thus

Case 2 shows the improvement achieved using the principles of the invention.

TABLE I

5

	Case 1 Fluctuation	Case 2 Fluctuation
Initial Fluctuation	10%	10%
First Reflection from Sagnac Mirror	10%	5%
After First Stage (10x Gain)	26%	12%
After Second Stage (5x Gain)	52%	22%
After Third Stage (2.5x Gain)	61%	22%

10

15

In the specific example illustrated in Table I we are considering only one noise burst, entered in the first step. The fluctuation is reduced to 1/3 by using the invention as is demonstrated by comparing the 61% fluctuation

20 in Case 1 with the 22% in Case 2.

The values in Table I are based on the following model. Assume that the systems compared in both cases start with a pump and then cascade three orders (e.g., 1117 nm pump, cascade to 1175 nm, 1240 nm and then 1310 nm). We can specify the gain at each successive order to be 1/2 of the previous order. A gain in the first step of 10 dB = 10x has been assumed. In this model the gain in the earlier stages is higher than in the later stages, because the earlier stages are robbed of power by the later stages during the cascading process. In general, the gain required at each stage for lasing is going to be such that the gain balances the loss. Thus, pumping higher orders corresponds to a loss and earlier stages must therefore have more gain. For simplicity, pump depletion and the resulting gain saturation have been neglected. Case 1 illustrates how a 10% noise fluctuation grows to a 61% fluctuation after three stages.

Case 2 shows how that same noise fluctuation is amplified only 22% due to the 50% rejection in the Sagnac mirror for the higher stages. In Table I, note that the initial 10% fluctuation is reduced to 5% upon first reflection from the 5 Sagnac mirror. This corresponds to 50% of the difference mode energy being rejected through the rejection port.

The equations used to generate the values shown in Table I will now be described with reference to Figures 3A and 3B. -In Figure 3A two optical signal paths are shown 10 being fed into and out from a 50:50 coupler. The input signals  $E_1$  and  $E_2$  produce output signals  $E_3$  and  $E_4$ , respectively according to the following equations:

$$E_3 = \frac{1}{\sqrt{2}}E_1 + j\frac{1}{\sqrt{2}}E_2$$

15

$$E_4 = j\frac{1}{\sqrt{2}}E_1 + \frac{1}{\sqrt{2}}E_2$$

20 In the above equations  $j = \sqrt{-1}$ , corresponding to the phase of  $\frac{\pi}{2}$ . Propagation through a fiber of length L is given by the following expression:

$$E_i e^{j\phi},$$

in which  $\phi$  corresponds to the following phase shift calculation:  
25

$$\phi = 2\frac{\pi}{\lambda} n L.$$

Figure 3b shows the signal propagation within a Sagnac loop mirror that comprises a 50:50 coupler. The input 30 electric field  $E_a$  is split at the coupler, propagating in clockwise and counterclockwise directions, corresponding to electric fields  $E_3$  and  $E_4$ . These fields are related to the input field  $E_a$  according to the following equations:

35

$$E_3 = \frac{1}{\sqrt{2}} \cdot E_{in}$$

$$E_4 = j \frac{1}{\sqrt{2}} \cdot E_{in}$$

5

The effect of the Sagnac loop mirror is to produce a reflected field  $E_{ref}$  that corresponds to the common mode of propagation, and to produce a rejected field  $E_{out}$  that corresponds to the difference mode of propagation. The 10 common mode and difference mode signals are thus described by the following equations:

$$E_{ref} = \frac{1}{2} j \{E_{clockwise} + E_{counterclockwise}\}$$

- common mode reflection

$$E_{out} = \frac{1}{2} \{E_{clockwise} - E_{counterclockwise}\}$$

- difference mode rejection

As the above Table shows, even a modest pump fluctuation (in 20 this example a 10% fluctuation) is multiplied again and again through each cascaded order. This is why Raman amplifiers have not been considered generally useful in the past. However, the invention overcomes this problem by adopting a structure that places the distributed gain medium in a 25 difference mode signal path, such that higher order pump fluctuations are at least partially rejected.

Figure 4 shows a second embodiment of the invention. A resonant cavity is formed between reflector 22 and reflector 24. Reflector 24 is a Sagnac interferometer 30 including a dichroic coupler 32b and a fiber loop. Dichroic coupler 32b is used to provide frequency selectivity. The dichroic coupler provides nominally 50:50 coupling over the cascade Raman order wavelengths, but a ratio that is closer to 100:0 for the signal wavelength. Thus, for a  $1.3 \mu\text{m}$  system the 50:50 coupling would be provided for wavelengths less than 1300 nm and the 100:0 coupling would be provided for wavelengths greater than 1300 nm. The advantage of this

configuration is that it is easier to make a balanced Sagnac interferometer, and the fiber in the Sagnac interferometer may be packaged more simply. One possible disadvantage of this configuration is that the dichroic coupler may be more difficult or expensive to implement. The signal input WDM port 42b is positioned in the cavity at a location between the two reflectors 22 and 24 and adjacent a WDM coupler 28. Polarization controllers 46 and 48 are used in the cavity and fiber loop, respectively. Polarization controllers may also be used in a similar fashion in the embodiment illustrated in Figure 2.

Figure 5 illustrates a third embodiment of the invention in which reflector 22 of Fig. 2 has been replaced by a series of grating reflectors 50 and 52. The grating filters may be selected to provide 100 percent reflection at selected wavelengths, such as at 1175 nm and 1240 nm. The advantage of the configuration of Figure 5 is that a narrow pump line width can be achieved. The disadvantage is that the configuration is more complicated and more expensive to fabricate.

Figure 6 illustrates yet a fourth embodiment in which the Sagnac reflector 24 is constructed using a coupler 32c having an unequal coupling ratio, for instance 60:40. By unbalancing the Sagnac reflector the system will tend to further reject noise bursts that randomly occur in the loop. This will serve to dampen out any mode locking or Q-switching tendencies. However, the unequal coupling leads to a leakage at various wavelengths, so that higher pump powers may be required to account for the reduced efficiency.

Figure 7a depicts a fifth embodiment of the invention which employs a Fabry-Perot wavelength filter 54 to narrowly select the Raman pump orders. In other respects the embodiment is the same as that of Fig. 2.

A detailed depiction of the Fabry-Perot filter is shown in Figure 7b. The fiber is split into two segments 56 and 58 and separated to define an air gap 60. The cleaved ends of the fiber segments are coated at 62 with a nominally

high selectivity coating ( $R > 90\%$ ) at the wavelengths of interest. The cleaved faces are aligned parallel to each other and piezoelectric transducers 64 may be used to adjust the air gap width. Ideally, the air gap width  $L$  can be  
5 adjusted so the free-spectral range of the Fabry-Perot interferometer ( $\Delta f = c/2nL$ ) will match the reflection at the various Raman orders (spaced by  $\Delta f = 13.2\text{THz}$ ). Thus a single Fabry-Perot interferometer can be used to replace the multiple gratings 50 and 52 of the Figure 5 embodiment,  
10 because the transmission function is a periodic function of frequency. For example, for an air gap index  $n = 1$ , the spacing should be  $11.36 \mu\text{m}$  for  $\Delta f = 13.2\text{THz}$ . Alternatively, the spacing may be some integer multiple of this fundamental width. The fiber Fabry-Perot interferometer can also be  
15 replaced with a bulk interference filter, which can be rotated to adjust the peak transmission frequencies.

### 3. Embodiments of Sagnac Raman Cascade Lasers

The above embodiments focus on using the optical  
20 resonator of the invention as an optical amplifier. Thus in the preceding examples, a signal input port is provided into which the signal to be amplified is injected. However, the invention is not limited to amplifiers. The invention can also be used to develop cascade oscillators or cascade  
25 lasers. Various configurations are now described for constructing Sagnac Raman cascade lasers.

Figure 8 illustrates a first embodiment of the Sagnac Raman cascade laser of the invention. In the laser, a fraction of the light at the desired wavelength is extracted  
30 from the cavity. The laser cavity comprises first and second reflectors 22, 24 wherein the second reflector is a Sagnac interferometer comprising a gain fiber 30 approximately 1 km long with enhanced Raman cross-section and a broad-band 50:50 coupler 31 at the base of the Sagnac gain fiber, and two  
35 wavelength-specific couplers 27 and 43 for bringing in the pump and removing the desired wavelength, respectively. A high-powered diode-array-cladding-pumped fiber laser 25

operating around  $1.1 \mu\text{m}$  pumps the Sagnac Raman laser. This is chosen because commercial units with continuous wave powers approaching 10W are available where the light launches directly into a single mode fiber. Then, a Sagnac cavity is used to permit the cascaded Raman process to downshift the pump at  $1.1 \mu\text{m}$  to the communications bands around  $1.3 \mu\text{m}$  (through a three-step cascade) or to  $1.55 \mu\text{m}$  (through a six-step cascade).

The cascaded Raman process allows for large and varied wavelength shift between the pump and signal wavelengths. The novel Saghac cavity design can dampen the noise fluctuations that would normally grow during the cascade process because the Sagnac mirror reflects common mode signals and dampens difference mode noise.

Figure 9 illustrates a second embodiment of the Sagnac Raman cascade laser of the invention. This embodiment is the same as that of Figure 8 but includes an intracavity coupler 66 that provides bidirectional outputs labeled  $\lambda_{\text{out}}$ . Advantageously, port 68 outputs a larger portion of the laser's total output than port 70 so the output at port 70 may be used for monitoring purposes.

Figure 10 illustrates a third embodiment of the Sagnac Raman cascade laser of the invention. This embodiment is the same as that of Fig. 8 but eliminates output coupler 43 by using a dichroic coupler 32d in the Sagnac loop mirror 24. The output of this oscillator  $\lambda_{\text{out}}$  exits from the external cavity port of the Sagnac loop mirror 24. The dichroic coupler can be selected to provide 50:50 coupling over the cascade order and 100:0 coupling at the  $\lambda_{\text{out}}$  wavelength.

Figure 11 shows a fourth embodiment of the Sagnac Raman cascade laser. This embodiment is the same as that of Fig. 8 but eliminates output coupler 43 by replacing mirror 22 with a dichroic mirror 72. Note that the dichroic mirror is reflective for cascade order wavelengths and is partially or completely transmitting for the  $\lambda_{\text{out}}$  wavelength.

The Sagnac Raman cascade lasers described in the preceding examples (Figures 8-11) may be used in numerous

applications, including upgrading existing fiber links, remote pumping of EDFAs, or other applications requiring different wavelengths of light. In this regard, the embodiments illustrated in Figures 8-11 are merely exemplary, 5 and there may be other possible configurations employing the principles of the invention.

#### 4. Broadband Raman Amplifiers Using Broadband Pumps

The basic idea to further broaden the bandwidth of 10 the Sagnac Raman amplifier and cascade laser is to take advantage of the property of Raman amplification that the gain spectrum follows the pump spectrum so long as there is nothing in the Raman laser cavity to restrict the bandwidth. Raman laser schemes using either gratings or wavelength 15 selective couplers cannot exploit this unique property of Raman amplification. Thus, the broadband cavity design of the Sagnac Raman amplifier and laser lends itself naturally to increased bandwidth by tailoring of the pump spectrum.

Figure 12 illustrates a general principle to form a 20 broadband pump. A bandwidth-adding mirror 110 is attached at the output end of a pump laser 100. The spectrum of the reflected signal is broader than the incident signal. Due to the nonlinear index-of-refraction in the fiber, the spectrum is broadened in the fiber through processes known as four- 25 wave mixing or self-phase modulation.

A numerical example can help illustrate the spectral broadening possible through either four-wave mixing or self-phase modulation. For instance, assume that we use a length of the fiber that would be used in a Sagnac Raman 30 laser or amplifier. Typical fiber parameters are as follows:

$$A_{\text{eff}} = 15 \mu\text{m}^2 \text{--- effective area}$$

$$n_2 / A_{\text{eff}} = 2 \times 10^{-9} \text{ W}^{-1} \text{ --- effective nonlinearity}$$

$$L = 1 \text{ km}$$

The nonlinear phase shift in the fiber is given by

$$\Delta\phi = \delta k L = \frac{2\pi}{\lambda} \delta n L = \frac{2\pi}{\lambda} L \frac{n_2}{A_{eff}} P.$$

5 Under the condition that the pump power in the fiber is 1W at the wavelength of 1.1  $\mu\text{m}$ , the resulting phase shift is  $\Delta\phi=3.6\pi$ . Figure 13 illustrates exemplary spectra resulting from self-phase modulation of Gaussian pulses, and similar spectral broadening can be expected from four-wave mixing.

10 In particular, the calculated self-phase modulation spectra are shown for an unchirped Gaussian pulse. The spectra are labeled by maximum phase shift at the peak of the pulse (after R.H. Stolen and C. Lin, *Physical Review A*, Vol. 17, p. 1448, 1978). The spectral broadening factor is approximately given by the numerical value of the maximum phase shift.

15 Therefore, in a single-pass transmission through the fiber, a spectral broadening of up to an order-of-magnitude might be expected. However, in closed loop operation in a laser cavity or oscillator, the spectral broadening will reach some steady-state value given by the counter-balance from spectral 20 broadening and narrowing forces. Furthermore, such a large phase shift will not be achieved because the pump intensity is depleted by the various Raman Stokes orders.

Therefore, following on the concept of replacing wavelength restrictive gratings in the Raman amplifier with broadband Sagnac loop mirrors, to achieve a broadband pump it would be desirable to place a Sagnac mirror at the output of the cladding-pumped fiber laser. Moreover, it would also be desirous to have a reflective element on the cladding-pumped fiber laser that actually adds bandwidth to the laser. This could be achieved by using a long fiber length in the Sagnac loop mirror and utilizing the fiber nonlinearities, as described further below.

Figure 14b illustrates a first embodiment of the broadband pump in which a Sagnac loop mirror 160 is placed at the output of a cladding-pumped fiber laser 150. Since there are no reflective surfaces in the loop, the Sagnac mirror can

handle the high powers from the cladding-pumped fiber laser without damage. As long as coupler 162 at the base of the loop is broadband, the reflectivity of the loop mirror can also be broadband. In addition, just as described for the 5 Sagnac Raman amplifier and lasers above, the Sagnac loop provides some noise rejection properties. To permit partial transmission of the output, however, the loop mirror must be imbalanced in one of several ways. First, the coupler 162 at the base of the Sagnac loop can have a coupling ratio other 10 than 50:50, which would lead to a certain amount of minimum leakage from the mirror. In particular, if the splitting ratio is  $(f:1-f)$  wherein  $0 \leq f \leq 1$ , then the reflection coefficient is  $4f(1-f)$  and the transmission coefficient is  $[1-4f(1-f)]$ . Also, the unequal coupling will lead to an 15 output associated with the fiber nonlinearities.

Alternately, the loop can be imbalanced by using a polarization controller 165.

Inserting some sort of modulation in the cavity, thus adding sidebands to the spectrum, could further increase 20 the bandwidth of the pump. Figure 14c is a second embodiment of the broadband pump where the modulation is produced by a phase or amplitude modulator 167 inserted asymmetrically into the Sagnac loop mirror. Alternately, modulation might be applied to the drive for the pump laser 155. For example, 25 the current drive to the diode lasers could be modulated, or different diodes could be excited as a function of time (i.e., excite one set of diodes alternately from another set). Finally, a mechanical modulation could be applied to the cladding-pumped fiber itself to perturb the longitudinal 30 modes and lead to additional multi-mode bandwidth.

The broadband pump can be combined with the Sagnac Raman amplifier to obtain the desired broadband gain spectrum. Figure 15a illustrates a first embodiment of the broadband Sagnac Raman amplifier of the invention that 35 combines the embodiment described in Figure 2 with the broadband pump of Figure 14. By separating the Raman amplifier from the broadband pump, the bandwidth of each

element can be individually optimized. The broadened bandwidth for the pump also increases the amount of pump power that can be injected into the cavity, since the limitations from stimulated Brillouin scattering will be 5 reduced. The amplifier resonant cavity is formed between reflector 22 and reflector 24. Reflector 24 is a Sagnac interferometer including a coupler 32 and a fiber loop 30. An input WDM port 42 is used to input an optical signal. The optical signal then exits from an output WDM port 44. The 10 WDM port 28 used to inject the pump, however, must not restrict the bandwidth of the pump light. That is, a sufficiently broadband WDM is required. The resulting bandwidth for the Raman gain should be the convolution of the pump spectrum with the spectrum from the Sagnac Raman 15 amplifier. For example, if the pump spectrum is 10 nm wide and the Sagnac Raman amplifier spectrum is also 10 nm, the gain spectrum resulting from the configuration of Figure 15a should be about 20 nm wide.

As an alternative from the configuration of Figure 20 15a, Figure 15b shows a second embodiment of the broadband Sagnac Raman amplifier in which a Sagnac mirror is used for both the pump linewidth broadening and the Raman amplification. Specifically, the Raman amplifier cavity is formed between the Sagnac mirror 160 and a reflector 170. A 25 pump laser 150 is connected to the rejection port of the Sagnac mirror. Instead of using a WDM to introduce the pump light to the gain medium of the Sagnac Raman cavity, the Sagnac loop itself is used to bring in the pump light. The reflector 170 could be a mirror or other equivalents 30 described earlier. The gain fiber of the Sagnac mirror is single mode not only at Raman order wavelengths but also at the pump wavelength, and the coupler at the base of the Sagnac mirror has similar characteristics for the pump and the Raman cascade orders.

35 Note that Figure 15b is shown by way of example. Any of the amplifier cavities in Figures 2 and 4-7 or the laser cavities of Figures 8-11 can also take advantage of the

pumping through the Sagnac configuration rather than using a separate WDM to bring in the pump light.

To accomplish the broadband pump through nonlinear spectral broadening and to achieve the broadband gain in the 5 Sagnac Raman amplifier or laser, a more preferred embodiment is to combine configurations of the Sagnac Raman amplifier and cascade laser with the broadband pump. Figures 16a and 16b schematically illustrate respectively preferred embodiments of a broadband Sagnac Raman cascade laser and 10 amplifier. The resonant cavity is formed between reflector 22 and reflector 24. Reflector 24 is a Sagnac interferometer including a coupler 32 and a fiber loop 30. An output WDM port 44 is used to exit an optical signal from the cavity. The 50:50 coupler 32 should have more-or-less flatband 15 response over the spectral range from the pump wavelength to the signal or output wavelength. A cladding-pumped fiber 174 or 179 is placed between two reflectors 22 and 24. A diode-array pump 172 or 177 pumps the cladding-pumped fiber 174 or 179 respectively. The diode-array pump is introduced by 20 using mirrors or lenses directly to one end of the fiber, or the fiber may have a dichroic mirror at the end and then the pump is injected through the end mirror. The cladding-pumped fiber generates a pumping light which subsequently pumps the fiber loop 30.

25 Such a cavity has the following advantages. first, broadband reflector plus spectral broadening from the fiber nonlinearities adds bandwidth at the pump wavelength. Second, there is a significant reduction in the number of components, hence a reduction in the manufacturing cost. 30 Third, the pump laser and the Raman unit are combined into a smaller unit thereby making smaller packaging possible.

One difficulty in implementing a WDM system using Raman amplifiers may be the wavelength dependent gain (see Figure 1b). This wavelength dependency or nonuniformity of 35 the gain band has little impact on single-channel transmission. However, it renders the amplifier unsuitable for multichannel operation through a cascade of amplifiers.

As different wavelengths propagate through a chain of amplifiers, they accumulate increasing discrepancies between them in terms of gain and signal-to-noise ratio. However, using gain-flattening elements can significantly increase the usable bandwidth of a long chain of amplifiers. Figure 17 shows that the Sagnac Raman amplifier in the above embodiments may be followed by such a gain flattening element 180 to provide gain equalization for different channels. Alternately, the gain flattening element could be introduced directly into the Sagnac interferometer loop.

Although several technologies have been proposed for gain equalization, to date the long period gratings appear to be the most promising candidates. Long period gratings are periodic structures formed in the core of a photosensitive optical fiber (c.f. S.K. Juma, 'Gain Flattening of EDFA for DWDM Systems,' *FiberOptic Product News*, pp. 17-20, June 1997, or A.M. Vengsarkar, 'Long-period fiber gratings shape optical spectra,' *Laser Focus World*, pp. 243-248, June 1996). Usually, the refractive index perturbations have a periodicity much greater than the wavelength of light, usually of the order of 200 to 400 microns, hence the 'long' in the name. Special design algorithms and simulation tools exist for modeling the filter response of the gratings. These filter characteristics can then serve as a basis for fabricating a combination of gratings to achieve the desired filter response.

##### 5. Broadband Sagnac Raman Amplifier and Cascade Laser Using Polarization Maintaining Fiber

To obtain the broadest bandwidth from the Sagnac amplifier cavity, the wavelength-selective elements in the cavity must be minimized. Thus far, in the cavity designs of the Sagnac Raman amplifier and cascade laser, the polarization controllers (PC) still remain wavelength dependent. The best solution for the Sagnac Raman cavity is to remove the need for PCs entirely.

One way of achieving this is to use an all-polarization-maintaining (PM) cavity. Figure 18a illustrates such an all-PM Sagnac Raman cavity that requires PM fiber as well as PM WDMs and couplers. As is apparent, this embodiment is the same as that of Figure 2 except that it uses PM fiber and PM WDMs and couplers. However, the PM fiber through which the signal travels might introduce polarization mode dispersion onto the channel. This can be avoided by mid-way through the cavity cross-splicing the fibers so the slow and fast axes are interchanged. Then, the second half of the cavity undoes the polarization mode dispersion in the first half of the cavity. If the polarization mode dispersion in half of the cavity causes too much signal degradation, then the cross-splicing can be done at more frequent intervals.

Although the optimal cavity would use PM fiber and PM components, alternate cavity designs can be used if such fibers or components are either not available or too expensive. The embodiment of Figure 18b has the same configuration as that of Figure 18a except that it uses a bulk 50:50 beam splitter 200. On the other hand, if the gain fiber cannot be made PM while retaining the other desired qualities in terms of Raman gain, then cavities such as Figures 19a or 19b can be used. In Figure 19a, the cavity is formed between reflector 22 and a Sagnac loop mirror 210.

The Sagnac loop mirror is made of a short length of standard or dispersion-shifted PM fiber. A Raman gain fiber 202 is placed in the middle of the cavity of the amplifier. Alternatively, two Sagnac loop mirrors are used as the two reflectors of the amplifier as depicted in Figure 19b. Note that similar modifications can be made to the configurations of Figures 8-11, 15 or 16 as have been made in Figures 18a, 18b, 19a and 19b to the Sagnac Raman cavity shown in Figure 2.

## 6. Noise Reduction through Polarization Diversity

The Sagnac Raman cavity design is also advantageous for reducing the deleterious effects of DRS. For example, at the 50:50 coupler 32 in Figure 2 or 8, the pump power is 5 split along the two directions. Since DRS is proportional to the pump intensity, this reduction in half of the power along each path reduces the DRS. Second, when the clockwise and counter-clockwise paths are combined interferometrically at the 50:50 coupler, the common mode signal will be reflected 10 while the difference mode noise will be partially rejected. Hence, the rejection port 46 in Figure 2 or 8 will also dampen the DRS.

An improvement on the Sagnac Raman amplifier design to further reduce the DRS is to use a polarization diversity 15 pumping scheme. In such a scheme, the pump power is split between the two orthogonal polarizations of the fiber, reducing in half the power per polarization. In addition to reducing DRS, this pumping scheme will also produce gain from the Raman amplifier that is independent of the input signal 20 polarization. This polarization independent gain property is highly desirable for most applications.

Figures 20a and 20b illustrate two embodiments of techniques to create the polarization diversity pumping. A pump laser 230, such as the cladding-pumped fiber laser, is 25 normally linearly polarized. As depicted in Figure 20a, pump laser 230 is coupled to a length of polarization maintaining fiber 240, where the light is coupled at 45 degrees to the fiber axes, and the birefringence of the PM fiber splits the two polarizations. The fiber can be rotated to accommodate 30 the launch angle, or a quarter or half-wave retarder 250 can be used at the entrance end of the PM fiber to adjust the polarization. Alternately, as shown in Figure 20b, a 50:50 coupler 260 is used to split the pump light into two beams. The polarization of one of the beams is then rotated by a 35 quarter or half-wave retarder 270, and the two beams are then combined using a polarization beam splitter 280. Once

separated along two axes, the pump light is then delivered to the Raman amplifier or laser configurations.

The polarization diversity scheme can be combined with other improvements disclosed earlier in the specification. For example, if an all-PM cavity is used as described in Figures 18a, 18b, 19a and 19b, then the linearly polarized pump light is adjusted to be launched at 45 degrees to the fiber principal axes. Alternately, if the integrated pump and Sagnac Raman amplifier is used as described in Figures 16a and 16b, then the axis of the cladding-pumped fiber 174 or 179 can be spliced at 45 degrees to the remainder of the cavity.

Figure 21 shows an embodiment of the polarization diversity pumping system of the invention in which a length of PM fiber 290 is inserted after a cladding-pumped fiber 295. In particular, the axis of the cladding-pumped fiber is spliced at 45 degrees to the fiber axis of the PM Sagnac loop. Alternately, a polarization maintaining fiber is inserted if the Sagnac loop is not polarization maintaining.

20

## 7. Two-Wavelength Amplifiers

Raman amplifiers as described herein can provide the necessary element of two-wavelength, broadband amplification. To illustrate the various orders of Raman amplification that can be involved in the amplification process, Table II provides exemplary cascade orders for Raman amplification of signals at either 1310 nm or 1550 nm. The pump is assumed to be a cladding-pumped fiber laser, which can be tuned to operate at 1100 nm or 1117 nm. Amplification of a signal at 1310 nm involves three cascaded Raman orders, while a signal at 1550 nm involves six cascaded Raman orders. However, the criteria for using such a device is that there should not be any degradation of the performance at 1550 nm when adding the window at 1310 nm, or vice versa.

35

TABLE II  
EXEMPLARY CASCADE ORDERS FOR RAMAN AMPLIFICATION

## (Peak Raman Gain at 13.2THZ)

## (a) 1310 nm amplification

$\lambda_p:$ <b>5</b> 1st:    1117 nm - pump 2nd:    1175 nm	}	wavelength from pump to two Raman orders below signal
3rd:    1310 nm -signal	}	One Raman order below signal

## (b) 1550 nm amplification

$\lambda_p:$ <b>10</b> 1st:    1100 nm - pump 2nd:    1155 nm 3rd:    1218 nm 4th:    1288 nm	}	wavelength from pump to two Raman orders below signal
<b>15</b> 5th:    1455 nm	}	One Raman order below signal
6th    1550 nm -signal		

There are several physical effects that should permit simultaneous support of signals at 1310 nm and 1550 nm. First, as illustrated in Table II, the amplification of 1310 nm signals requires three cascaded orders of Raman gain, while the amplification of 1550 nm signals requires six cascaded orders. Since there are at least two intermediate orders of Raman gain in the cascade, the Raman gain or cross-talk penalty between signals at  $1310 \mu\text{m}$  and  $1550 \mu\text{m}$  should be minimal. However, to avoid any interaction through pump depletion effects, it would be better to use Raman cascaded orders in two separate amplifier cavities. Moreover, the dispersion difference between signals at  $1310 \mu\text{m}$  and  $1550 \mu\text{m}$  will be quite large, typically about 16 psec/nm-km in standard or dispersion-shifted fiber. The large amount of group-velocity dispersion should lead to minimal nonlinear cross-talk between the two windows. For example, the four-wave mixing penalty will be minimal because the large dispersion leads to poor phase-matching. Also, the large

dispersion leads to a rapid walk-off between pulses at the two wavelengths, so the interaction length will be short.

The two-wavelength optical fiber amplifier can be implemented on the improvements described in this application 5 as well as on the basic framework of the Sagnac Raman amplifier. To avoid cross-talk through pump depletion, the two wavelengths should be amplified in parallel. However, since the pump laser is the most expensive part of the amplifiers, to the extent possible the pump laser should be 10 shared.

Figures 22a -22c illustrate several preferred embodiments of the two-wavelength amplifier. In all of these configurations, 1310/1550 nm WDMs are used to separate the incoming signals and then eventually combine the amplified 15 signals. In Figure 22a, two Sagnac Raman amplifiers such as that of Figure 2 are used in parallel to form the two-wavelength amplifier. The 1310 nm amplifier comprises a reflector 308 and a Sagnac loop mirror 310 having a loop and a coupler attached at the base of the loop. Similarly the 20 1550 nm amplifier comprises a reflector 314 and a Sagnac loop mirror 320 having a loop and a coupler attached at the base of the loop. Both the 1310 nm and 1550 nm amplifiers are powered by a common pump laser 305 through couplers 306 and 312 respectively. An input optical signal is divided into 25 two beams by a WDM 330, and the two beams are sent to input ports of the 1310 nm and 1550 nm amplifiers respectively. After amplification by these amplifiers, the output signals from each of the amplifiers are combined by a WDM 340. Note that to change the operating wavelength of the Sagnac 30 amplifier, the wavelength specifications for the 50:50 coupler 310 or 320 and the WDM couplers 330 and 340 for injecting and removing the signal must be adjusted.

Because of the high efficiency and mature technology of EDFA's, it may alternately be desirable to use 35 an EDFA to amplify the signal channel at 1550 nm. Figures 22b and 22c illustrate two exemplary configurations for employing a combination of Raman amplifiers and EDFA's. In

Figure 22b, a two-wavelength amplifier comprises a Sagnac Raman amplifier 350 to amplify a 1310 nm signal and an EDFA 370 to amplify a 1550 nm signal. The Sagnac Raman amplifier has the same configuration as that depicted in Figure 2 which primarily comprises two reflectors, one of which is a Sagnac loop mirror. The EDFA is pumped by a Sagnac Raman cascade laser 360 such as in Figure 8 that generates a 1480 nm light. The Sagnac Raman amplifier and cascade laser share a common pump laser 380.

Finally, Figure 22c illustrates a two-wavelength amplifier that comprises a Sagnac Raman amplifier 390 to amplify a 1310 nm signal and an EDFA 400 to amplify a 1550 nm signal. The Sagnac Raman amplifier has the same configuration as that depicted in Figure 2 which primarily comprises two reflectors, one of which is a Sagnac loop mirror. The EDFA 400 is pumped by its own 980 nm or 1480 nm pump unit 410. Since the pump laser is the single most expensive element in a typical EDFA or Raman amplifier, one advantage of the shared pump of Figures 22a or 22b will be reduced cost of the unit. However, the configuration of Figure 22c may also be advantageous when upgrading an existing 1550 nm amplifier unit. It should be clear that the Sagnac Raman amplifiers and lasers pictured in Figures 22a-22c can embody any of the improvements, such as broadband response and lower noise spectrum, discussed elsewhere in this patent.

It should be noted that the gain for the two channels and the division of the power of the shared pump may be different for the parallel paths. For example, as shown in the loss curve of Figure 1a, the loss around 1550 nm is typically about 0.2 dB/km, while the loss around 1310 nm is typically about 0.35 dB/km. Therefore, for the same spacing of amplifiers at 1310 nm and 1550 nm in a fiber-optic link, the amplifier at 1310 nm will have to provide more gain than the 1550 nm unit. Moreover, since the Raman amplifier at 1550 nm (six orders) or 1480 nm (five orders) requires more cascaded orders than when operated at 1310 nm (three orders),

the pump power to achieve the same gain level will be higher as the wavelength increases. Consequently, adjusting the splitting ratio of the pump to the two units can satisfy the different pumping requirements. Alternately, note from Table 5 II that there may be different optimal pump wavelengths to reach specific end gain windows. Therefore, a broadband pump such as those described in Figures 14a-14c might be divided spectrally using wavelength selective elements (i.e., gratings, WDMs or filters) rather than on the basis of power.

10 While the present invention has been described in a number of different exemplary embodiments, it will be understood that the principles of the invention can be extended to still further embodiments and that the 15 embodiments illustrated here are not intended to limit the scope of the invention as set forth in the appended claims.

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What Is Claimed Is:

1. A broadband Sagnac Raman amplifier comprising:
  - a first reflector;
  - a second reflector comprising a Sagnac loop mirror

5 fabricated from a distributed gain medium and a coupling means connected to two ends of said Sagnac loop mirror, said first reflector and said second reflector forming an optical resonator therebetween;

  - an input port for inputting an optical signal to

10 said distributed gain medium;

  - a pumping means for generating a pumping light to pump said distributed gain medium; and
  - an output port for outputting said optical signal from said distributed gain medium.

15

2. The broadband Sagnac Raman amplifier according to claim 1, wherein said pumping means is a broadband pump comprising:

20 a pump laser having an output port; and

a bandwidth adding mirror connected to said output port to generate a broadened pump spectrum.

3. The broadband Sagnac Raman amplifier according to claim 2, wherein said bandwidth adding mirror comprises a
- 25 Sagnac loop mirror.

4. The broadband Sagnac Raman amplifier according to claim 3, wherein said bandwidth adding mirror further comprises a coupler with an unequal ratio.

30

5. The broadband Sagnac Raman amplifier according to claim 4, wherein said coupler has a ratio of  $f:(1-f)$ , and  $0 \leq f \leq 1$ .

- 35 6. The broadband Sagnac Raman amplifier according to claim 3, wherein said bandwidth adding mirror further

comprises a polarization controller located within said Sagnac loop mirror.

7. The broadband Sagnac Raman amplifier according  
5 to claim 3, wherein said bandwidth adding mirror further  
comprises a phase modulator asymmetrically located within  
said Sagnac loop mirror.

8. The broadband Sagnac amplifier according to  
10 claim 3, wherein said bandwidth adding mirror further  
comprises an amplitude modulator asymmetrically located  
within said Sagnac loop mirror.

9. The broadband Sagnac Raman amplifier according  
15 to claim 2, wherein said pump laser is a cladding pumped  
fiber laser.

10. The broadband Sagnac Raman amplifier according  
to claim 9, wherein said cladding pumped fiber laser is  
20 driven by a modulated pump drive.

11. The broadband Sagnac Raman amplifier according  
to claim 9, wherein a mechanical modulation is applied to  
said cladding pumped fiber.

25

12. The broadband Sagnac Raman amplifier according  
to claim 1, wherein said distributed gain medium comprises  
polarization maintaining fibers cross-spliced at a joint in  
said Sagnac loop mirror and said coupling means is  
30 polarization maintaining, and said polarization maintaining  
fibers interchange polarization axes at the cross-splicing  
joint.

13. The broadband Sagnac Raman amplifier according  
35 to claim 12, wherein said coupling means is a coupler having  
a ratio of 50:50.

14. The broadband Sagnac Raman amplifier according to claim 12, wherein said coupling means is a bulk 50:50 beam splitter.

5 15. The broadband Sagnac Raman amplifier according to claim 12, wherein said pumping means is a broadband pump comprising a pump laser and a bandwidth adding mirror attached thereto.

10 16. The broadband Sagnac Raman amplifier according to claim 12, wherein said input and output ports are polarization maintaining WDMs.

15 17. The broadband Sagnac Raman amplifier according to claim 1, wherein said pumping means comprises:

a pump laser generating a linearly polarized pumping light; and  
a polarization maintaining fiber,  
said pumping light being launched at a 45 degree  
20 angle into said polarization maintaining fiber to produce a beam having two polarization directions.

18. The broadband Sagnac Raman amplifier according to claim 1, wherein said pumping means comprises:

25 a pump laser generating a linearly polarized pumping light;  
a polarization maintaining fiber; and  
a quarter wavelength plate located between said pumping means and said polarization maintaining fiber such  
30 that said polarization maintaining fiber produces a beam having two polarization directions.

19. The broadband Sagnac Raman amplifier according to claim 1, wherein said pumping means comprises:

35 a pump laser generating a linearly polarized pumping light;

a 50:50 coupler dividing said pumping light into a first beam and a second beam;

a retarder located in the path of said first beam to change the polarization direction of said first beam; and

5 a polarization beam splitter for combining said first beam and said second beam to produce a beam having two polarization directions.

20. The broadband Sagnac Raman amplifier according  
10 to claim 19, wherein said retarder is a half-wave plate.

21. The broadband Sagnac Raman amplifier according  
to claim 19, wherein said retarder is a quarter-wave plate.

15 22. The broadband Sagnac Raman amplifier according  
to claim 1, wherein said pumping means comprises:

a pump laser generating a pumping light;

a cladding-pumped fiber having two ends, one end  
being pumped by said pumping light;

20 a polarization maintaining fiber spliced at a 45  
degree angle to the other end of said cladding-pumped fiber  
to output from said polarization maintaining fiber a beam  
having two polarization directions.

25 23. A broadband Sagnac Raman cascade laser  
comprising:

a first reflector;

a second reflector comprising a Sagnac loop mirror  
fabricated from a distributed gain medium and a coupling  
30 means connected to two ends of said Sagnac loop mirror, said  
first reflector and said second reflector forming an optical  
resonator therebetween;

a pumping means for generating a pumping light to  
pump said distributed gain medium; and

35 an output port for outputting an optical signal  
from said distributed gain medium.

24. The broadband Sagnac Raman cascade laser according to claim 23, wherein said pumping means is a broadband pump comprising:  
a pump laser having an output port; and  
5 a bandwidth adding mirror connected to said output port to generate a broadened pump spectrum.

25. The broadband Sagnac Raman cascade laser according to claim 24, wherein said bandwidth adding mirror 10 comprises a Sagnac loop mirror.

26. The broadband Sagnac Raman cascade laser according to claim 25, wherein said bandwidth adding mirror further comprises a coupler with an unequal ratio.

15 27. The broadband Sagnac Raman cascade laser according to claim 26, wherein said coupler has a ratio of  $f:(1-f)$ , and  $0 \leq f \leq 1$ .

20 28. The broadband Sagnac Raman cascade laser according to claim 25, wherein said bandwidth adding mirror further comprises a polarization controller located within said Sagnac loop mirror.

25 29. The broadband Sagnac Raman cascade laser according to claim 25, wherein said bandwidth adding mirror further comprises a phase modulator asymmetrically located within said Sagnac loop mirror.

30 30. The broadband Sagnac Raman cascade laser according to claim 25, wherein said bandwidth adding mirror further comprises an amplitude modulator asymmetrically located within said Sagnac loop mirror.

35 31. The broadband Sagnac Raman cascade laser according to claim 24, wherein said pump laser is a cladding pumped fiber laser.

32. The broadband Sagnac Raman cascade laser according to claim 31, wherein said cladding pumped fiber laser is driven by a modulated pump drive.

5 33. The broadband Sagnac Raman cascade laser according to claim 31, wherein a mechanical modulation is applied to said cladding pumped fiber.

34. The broadband Sagnac Raman cascade laser  
10 according to claim 23, wherein said distributed gain medium comprises polarization maintaining fibers cross-spliced at a joint in said Sagnac loop mirror and said coupling means is polarization maintaining, and said polarization maintaining fibers interchange polarization axes at the cross-splicing  
15 joint.

35. The broadband Sagnac Raman cascade laser according to claim 34, wherein said coupling means is a coupler having a ratio of 50:50.

20 36. The broadband Sagnac Raman cascade laser according to claim 34, wherein said coupling means is a bulk 50:50 beam splitter.

25 37. The broadband Sagnac Raman cascade laser according to claim 34, wherein said pumping means is a broadband pump comprising a pump laser and a bandwidth adding mirror attached thereto.

30 38. The broadband Sagnac Raman cascade laser according to claim 34, wherein said output port is a polarization maintaining WDM.

35 39. A broadband pump, comprising:  
a pump laser having an output port; and  
a bandwidth adding mirror connected to said output port to generate a broadened pump spectrum.

40. The broadband pump according to claim 39,  
wherein said bandwidth adding mirror comprises a Sagnac loop  
mirror.

5 41. The broadband pump according to claim 40,  
wherein said bandwidth adding mirror further comprises a  
coupler with an unequal ratio.

10 42. The broadband pump according to claim 41,  
wherein said coupler has a ratio of  $f:(1-f)$ , and  $0 \leq f \leq 1$ .

15 43. The broadband pump according to claim 40,  
wherein said bandwidth adding mirror further comprises a  
polarization controller located within said Sagnac loop  
mirror.

20 44. The broadband pump according to claim 40,  
wherein said bandwidth adding mirror further comprises a  
phase modulator asymmetrically located within said Sagnac  
loop mirror.

25 45. The broadband pump according to claim 40,  
wherein said bandwidth adding mirror further comprises an  
amplitude modulator asymmetrically located within said Sagnac  
loop mirror.

46. The broadband pump according to claim 39,  
wherein said pump laser is a cladding pumped fiber laser.

30 47. The broadband pump according to claim 46,  
wherein said cladding pumped fiber laser is driven by a  
modulated pump drive.

35 48. The broadband pump according to claim 46,  
wherein a mechanical modulation is applied to said cladding  
pumped fiber.

49. A broadband Sagnac Raman cascade laser comprising:  
a first reflector;  
a second reflector comprising a Sagnac loop mirror  
5 fabricated from a distributed gain medium and a coupler  
connected to two ends of said Sagnac loop mirror, said first  
reflector and said second reflector forming an optical  
resonator therebetween;  
.. a cladding-pumped fiber located in said optical  
10 resonator;  
a pumping means for generating a pumping light to  
pump said cladding-pumped fiber; and  
an output port for outputting an optical signal  
from said distributed gain medium.

15

50. The broadband Sagnac Raman cascade laser according to claim 49, wherein said coupler has a ratio of 50:50.

20

51. The broadband Sagnac Raman cascade laser according to claim 49, wherein said pumping means is a diode pump array.

52. The broadband Sagnac Raman cascade laser  
25 according to claim 49, further comprising a polarization controller.

53. The broadband Sagnac Raman cascade laser according to claim 49, wherein said output port is a WDM.  
30

54. A broadband Sagnac Raman amplifier comprising:  
a first reflector;  
a second reflector comprising a Sagnac loop mirror  
fabricated from a distributed gain medium and a coupler  
35 connected to two ends of said Sagnac loop mirror, said first  
reflector and said second reflector forming an optical  
resonator therebetween;

an input port for inputting an optical signal to said distributed gain medium;

a cladding-pumped fiber located in said optical resonator;

5 a pumping means for generating a pumping light to pump said cladding-pumped fiber; and

an output port for outputting said optical signal from said distributed gain medium.

10 55. The broadband Sagnac Raman amplifier according to claim 54, wherein said coupler has a ratio of 50:50.

56. The broadband Sagnac Raman amplifier according to claim 54, wherein said pumping means is a diode pump  
15 array.

57. The broadband Sagnac Raman amplifier according to claim 54, further comprising a polarization controller.

20 58. The broadband Sagnac Raman amplifier according to claim 54, wherein said input port and output port are WDMs.

25 59. The broadband Sagnac Raman amplifier according to claim 54, further comprising a gain flattening element connected to said output port.

60. A broadband Sagnac Raman amplifier comprising:  
a first reflector;  
30 a second reflector comprising a Sagnac loop mirror fabricated from a distributed gain medium and a coupler connected to two ends of said Sagnac loop mirror, said first reflector and said second reflector forming an optical resonator therebetween;  
35 an input port for inputting an optical signal to said distributed gain medium;

a pumping means for generating a pumping light to pump said distributed gain medium, said pumping means being connected to one of said two ends of said Sagnac loop mirror; and

- 5 an output port for outputting said optical signal from said distributed gain medium.

61. The broadband Sagnac Raman amplifier according to claim 60, wherein said coupler has a ratio of 50:50.

10

62. The broadband Sagnac Raman amplifier according to claim 60, wherein said pumping means is a pump laser.

15 63. The broadband Sagnac Raman amplifier according to claim 60, further comprising a polarization controller.

64. The broadband Sagnac Raman amplifier according to claim 60, wherein said input port and output port are WDMs.

20

65. A broadband Sagnac Raman cascade laser comprising:

a first reflector;

25 a second reflector comprising a Sagnac loop mirror fabricated from a distributed gain medium and a coupler connected to two ends of said Sagnac loop mirror, said first reflector and said second reflector forming an optical resonator therebetween;

30 a pumping means for generating a pumping light to pump said distributed gain medium, said pumping means being connected to one of said two ends of said Sagnac loop mirror; and

an output port for outputting an optical signal from said distributed gain medium.

35

66. The broadband Sagnac Raman cascade laser according to claim 65, wherein said coupler has a ratio of 50:50.

5 67. The broadband Sagnac Raman cascade laser according to claim 65, wherein said pumping means is a pump laser.

10 68. The broadband Sagnac Raman cascade laser according to claim 65, further comprising a polarization controller.

15 69. The broadband Sagnac Raman cascade laser according to claim 65, wherein said output port is a WDM.

70. A broadband Sagnac Raman amplifier comprising:  
a first reflector;  
a second reflector comprising a Sagnac loop mirror fabricated from a polarization maintaining fiber and a  
20 coupler connected to two ends of said Sagnac loop mirror,  
said first reflector and said second reflector forming an optical resonator therebetween;  
a Raman gain fiber located in said optical resonator;  
25 an input port for inputting an optical signal to said distributed gain medium;  
a pumping means for generating a pumping light to pump said Raman gain fiber; and  
an output port for outputting said optical signal  
30 from said distributed gain medium.

71. The broadband Sagnac Raman amplifier according to claim 70, wherein said coupler has a ratio of 50:50.

35 72. The broadband Sagnac Raman amplifier according to claim 70, wherein said Sagnac loop mirror comprises a dispersion-shifted polarization maintaining fiber.

73. The broadband Sagnac Raman amplifier according to claim 70, wherein said pumping means is a broadband pump comprising

5           a pump laser having an output port; and  
              a bandwidth adding mirror attached to said output port.

74. The broadband Sagnac Raman amplifier according to claim 70, wherein said input port and output port are  
10 polarization maintaining WDMs.

75. The broadband Sagnac Raman amplifier according to claim 70, wherein said first reflector comprises a Sagnac loop mirror fabricated from a polarization maintaining fiber  
15 and a coupler connected to two ends of said Sagnac loop mirror.

76. The broadband Sagnac Raman amplifier according to claim 75, wherein said coupler of said first reflector has  
20 a ratio of 50:50.

77. The broadband Sagnac Raman amplifier according to claim 75, wherein said Sagnac loop mirror of said first reflector comprises a dispersion-shifted polarization  
25 maintaining fiber.

78. A polarization diversity pumping system,  
comprising:

30           a pumping means generating a linearly polarized pumping light; and

              a polarization maintaining fiber,  
              said pumping light being launched at a 45 degree angle into said polarization maintaining fiber to produce a beam having two polarization directions.

35

79. The polarization diversity pumping system according to claim 78, wherein said pumping means is a laser.

80. A polarization diversity pumping system, comprising:

a pumping means generating a linearly polarized pumping light;

5 a polarization maintaining fiber; and

a quarter wavelength plate located between said pumping means and said polarization maintaining fiber such that said polarization maintaining fiber produces a beam having two polarization directions.

10

81. The polarization diversity pumping system according to claim 80, wherein said pump means is a laser.

82. A polarization diversity pumping system, 15 comprising:

a pumping means generating a linearly polarized pumping light;

a 50:50 coupler dividing said pumping light into a first and second beams;

20 a retarder located in the path of said first beam to change the polarization direction of said first beam; and  
a polarization beam splitter for combining said first and second beams to produce a beam having two polarization directions.

25

83. The polarization diversity pumping system according to claim 82, wherein said pump means is a laser.

84. The polarization diversity pumping system 30 according to claim 82, wherein said retarder is a half-wave plate.

85. The polarization diversity pumping system according to claim 82, wherein said retarder is a quarter- 35 wave plate.

86. A polarization diversity pumping system, comprising:

a pumping means generating a pumping light;

a cladding-pumped fiber having two ends, one end

5 being pumped by said pumping light;

a polarization maintaining fiber spliced at a 45 degree angle to the other end of said cladding-pumped fiber to output from said polarization maintaining fiber a beam having two polarization directions.

10

87. A two-wavelength broadband Sagnac Raman amplifier, comprising:

a separating means for separating an optical signal to be amplified into a first and second beams, said first 15 beam having a different wavelength from said second beam; a first broadband Sagnac Raman amplifier comprising a first reflector; a second reflector comprising a Sagnac loop mirror fabricated from a distributed gain medium and a 20 coupling means connected to two ends of said Sagnac loop mirror, said first reflector and said second reflector forming an optical resonator therebetween;

an input port for inputting said first beam to said distributed gain medium; and

25 an output port for outputting said first beam from said distributed gain medium;

a second broadband Sagnac Raman amplifier comprising

a first reflector;

30 a second reflector comprising a Sagnac loop mirror fabricated from a distributed gain medium and a coupling means connected to two ends of said Sagnac loop mirror, said first reflector and said second reflector forming an optical resonator therebetween;

35 an input port for inputting said second beam to said distributed gain medium; and

an output port for outputting said second beam from said distributed gain medium;

a pumping means for generating a pumping light to pump said distributed gain mediums of said first and second 5 broadband Sagnac Raman amplifiers; and

a combining means for combining said first and second beams.

88. The two-wavelength broadband Sagnac Raman 10 amplifier according to claim 87, wherein said first broadband Sagnac Raman amplifier is operated at a wavelength of approximately 1310 nm.

89. The two-wavelength broadband Sagnac Raman 15 amplifier according to claim 87, wherein said second broadband Sagnac Raman amplifiers is operated at a wavelength of approximately 1550 nm.

90. A two-wavelength broadband Sagnac Raman 20 amplifier, comprising:

a separating means for separating an optical signal to be amplified into a first and second beams, said first beam having a different wavelength from said second beam;

25 a broadband Sagnac Raman amplifier comprising a first reflector;

a second reflector comprising a Sagnac loop mirror fabricated from a distributed gain medium and a coupling means connected to two ends of said Sagnac loop mirror, said first reflector and said second reflector 30 forming an optical resonator therebetween;

an input port for inputting said first beam to said distributed gain medium; and

an output port for outputting said first beam from said distributed gain medium;

35 an erbium-doped fiber amplifier having an input port and an output port, said input port receiving said second beam;

a Sagnac Raman cascade laser for pumping said erbium-doped fiber amplifier comprising

a first reflector;

a second reflector comprising a Sagnac loop

5 mirror fabricated from a distributed gain medium and a coupling means connected to two ends of said Sagnac loop mirror, said first reflector and said second reflector forming an optical resonator therebetween; and

10 an output port for outputting a pumping beam from said distributed gain medium, wherein said pumping beam pumping said erbium-doped fiber amplifier;

a pumping means for generating a pumping light to pump said distributed gain media of said broadband Sagnac Raman amplifier and said Sagnac Raman cascade laser; and

15 15 a combining means for combining said first beam and said second beam from said distributed gain medium of said broadband Sagnac Raman amplifier and said erbium-doped fiber amplifier respectively.

20 91. The two-wavelength broadband Sagnac Raman amplifier according to claim 90, wherein said broadband Sagnac Raman amplifier is operated at a wavelength of approximately 1310 nm.

25 92. The two-wavelength broadband Sagnac Raman amplifier according to claim 90, wherein said Sagnac Raman cascade laser produces a pumping beam having a wavelength of approximately 1480 nm.

30 93. A two-wavelength broadband Sagnac Raman amplifier, comprising:

a separating means for separating an optical signal to be amplified into a first beam and a second beam, said first beam having a different wavelength from said second beam;

a broadband Sagnac Raman amplifier comprising a first reflector;

a second reflector comprising a Sagnac loop mirror fabricated from a distributed gain medium and a coupling means connected to two ends of said Sagnac loop mirror, said first reflector and said second reflector  
5 forming an optical resonator therebetween;

an input port for inputting said first beam to said distributed gain medium; and

a pumping means for generating a pumping light to pump said distributed gain medium;

10 an output port for outputting said first beam from said distributed gain medium;

an erbium-doped fiber amplifier having an input port and an output port, said input port receiving said second beam; and

15 a combining means for combining said first beam and said second beam from said distributed gain medium of said broadband Sagnac Raman amplifier and said erbium-doped fiber amplifier respectively.

20 94. The two-wavelength broadband Sagnac Raman amplifier according to claim 93, wherein said broadband Sagnac Raman amplifier is operated at a wavelength of approximately 1310 nm.

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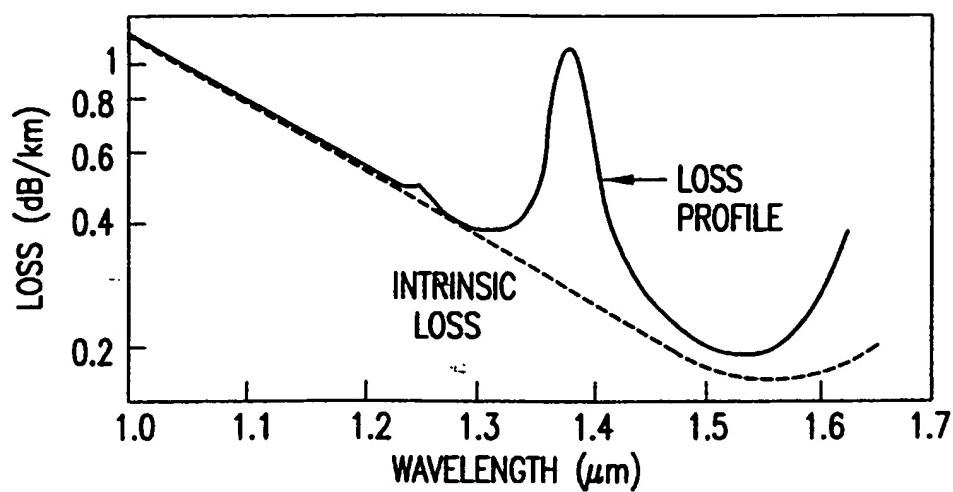


FIG.1a  
PRIOR ART

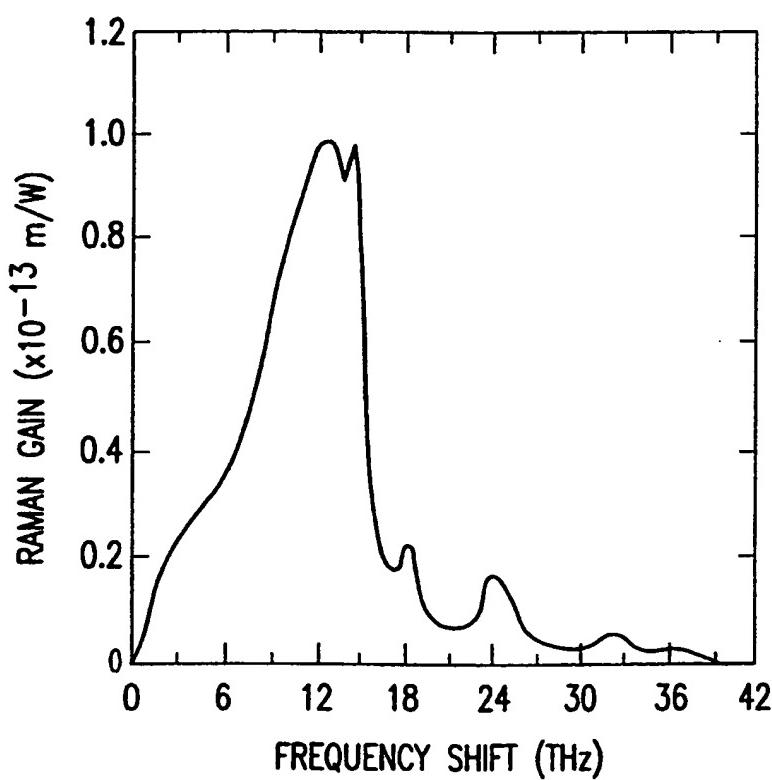


FIG.1b  
PRIOR ART

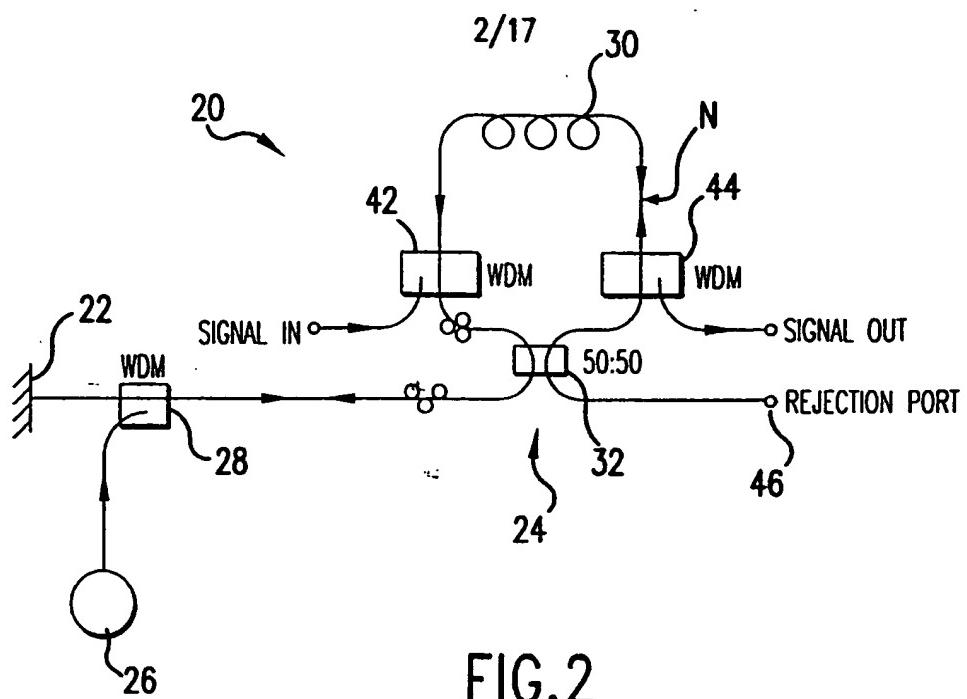


FIG.2

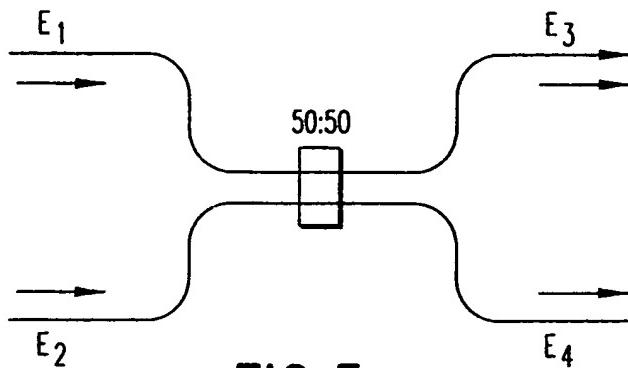


FIG.3a

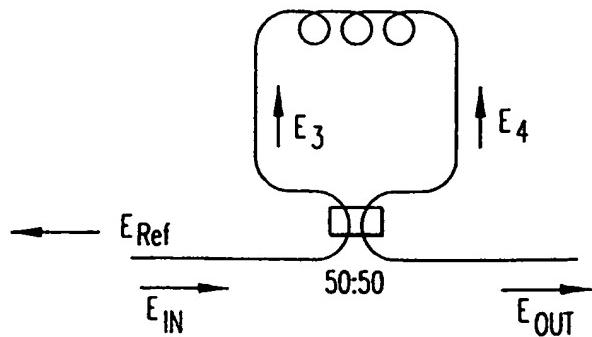


FIG.3b

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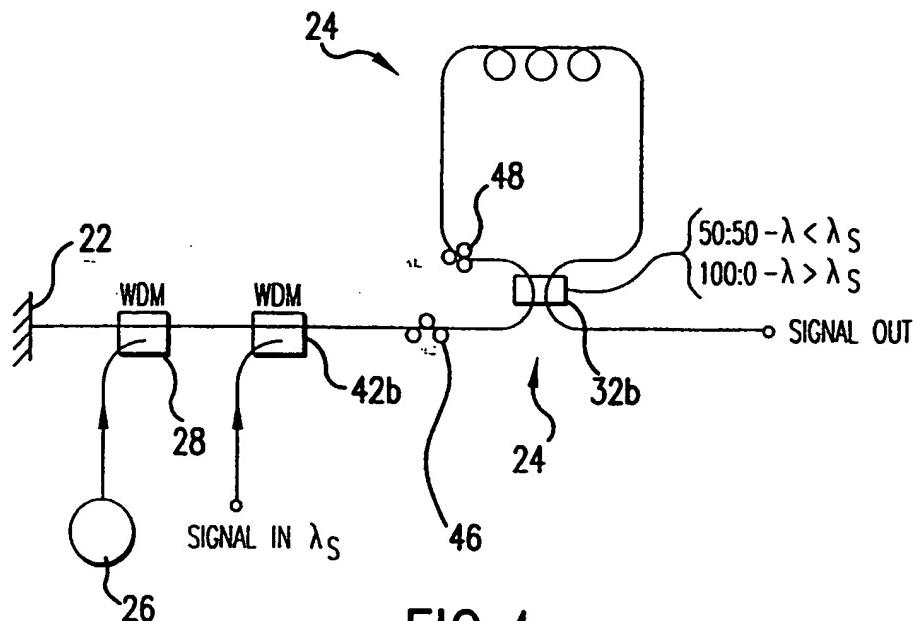


FIG.4

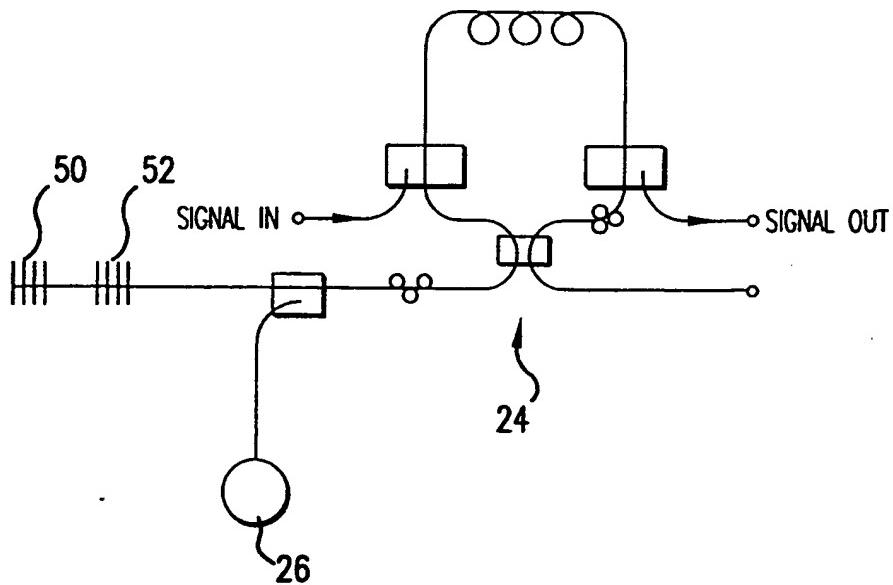


FIG.5

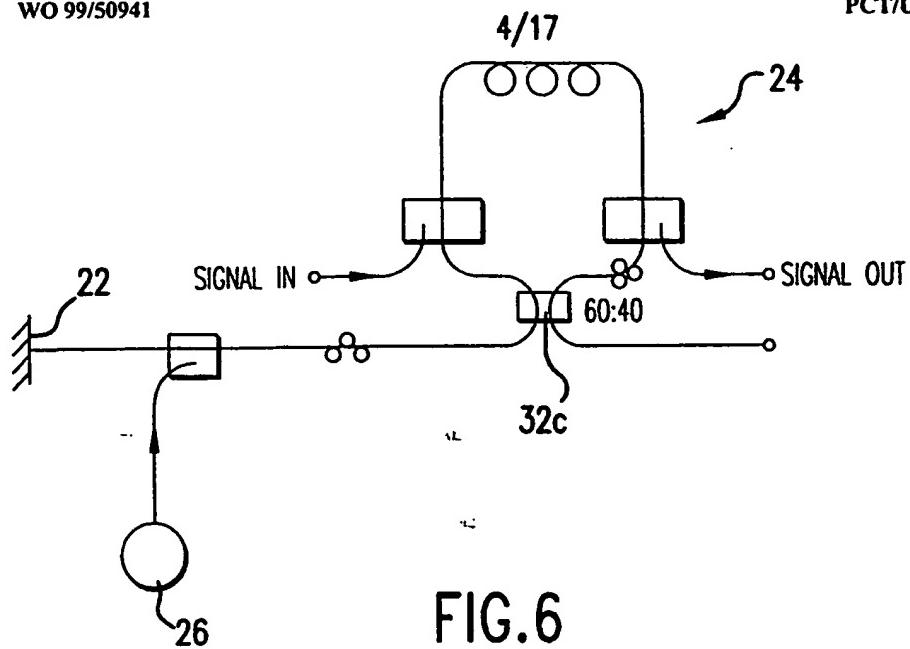


FIG. 6

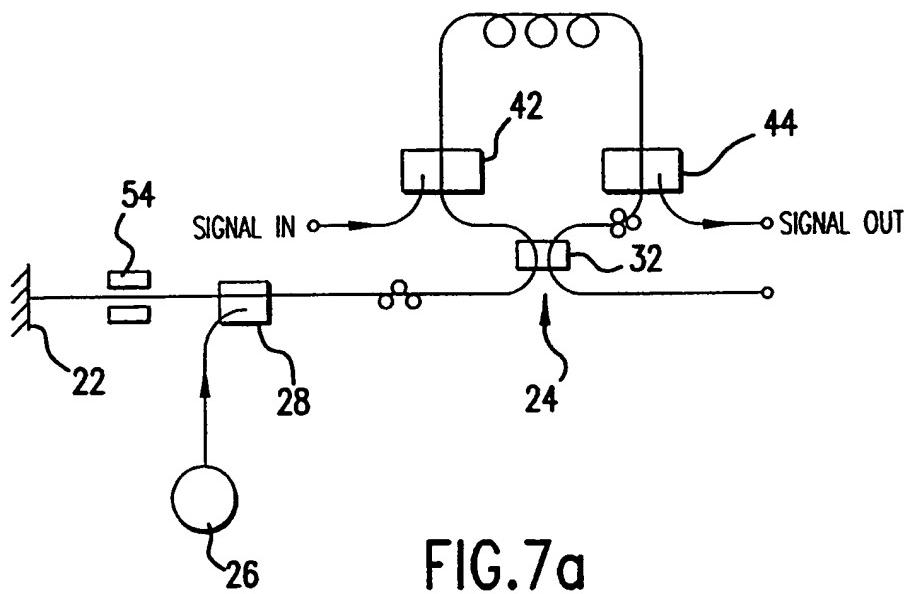


FIG. 7a

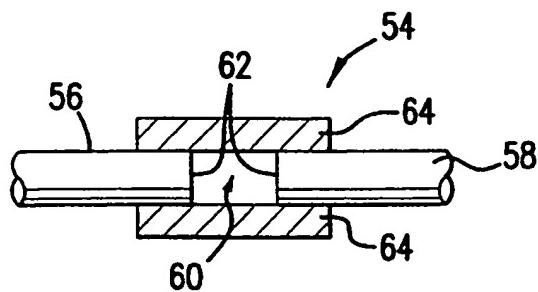


FIG. 7b

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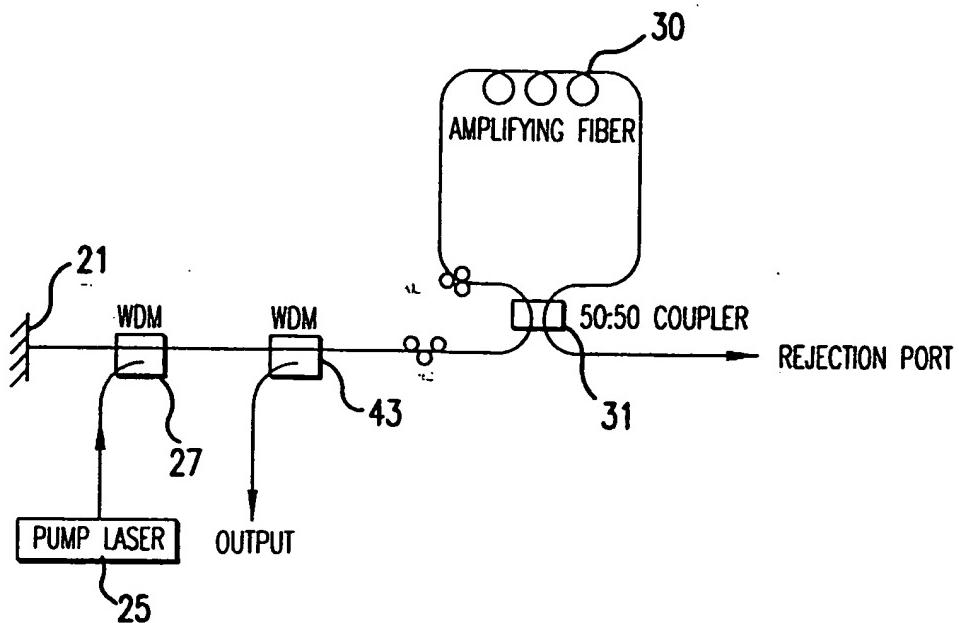


FIG.8

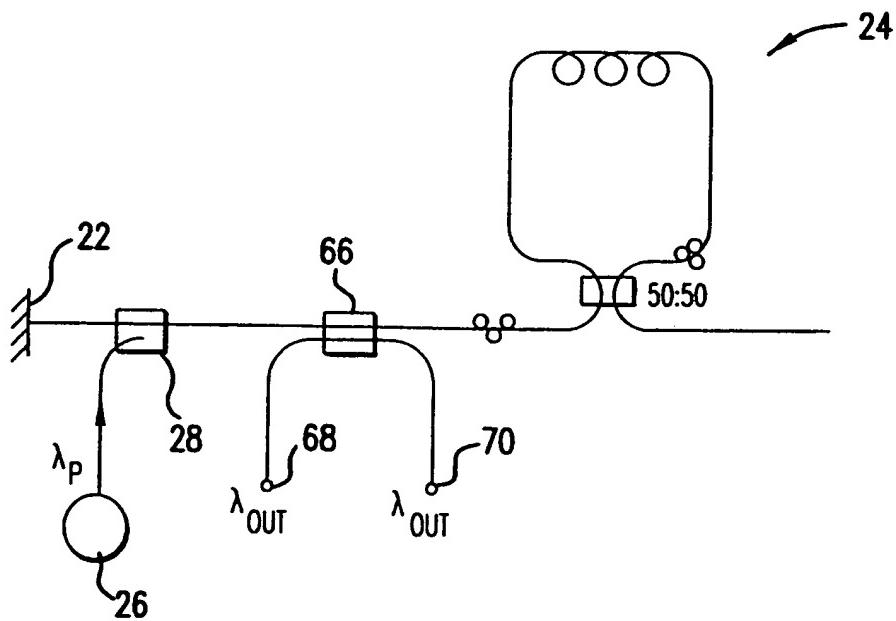


FIG.9

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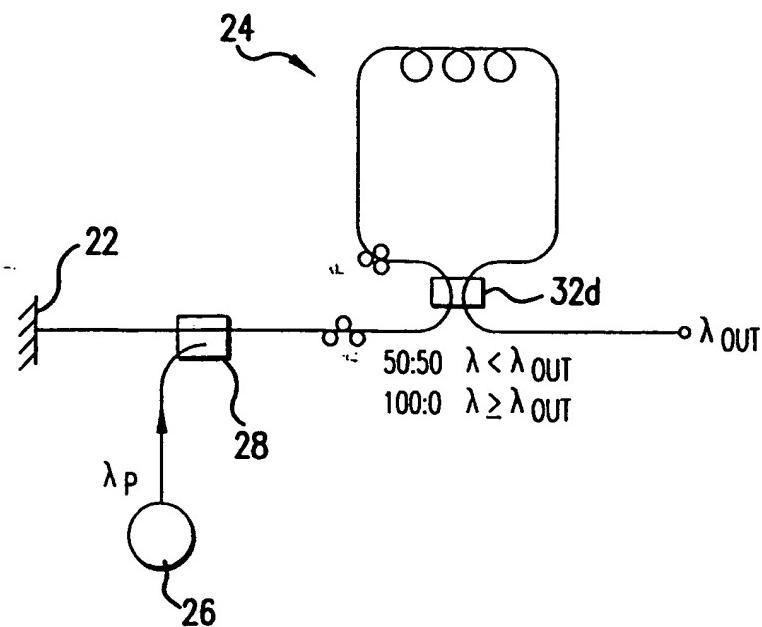


FIG.10

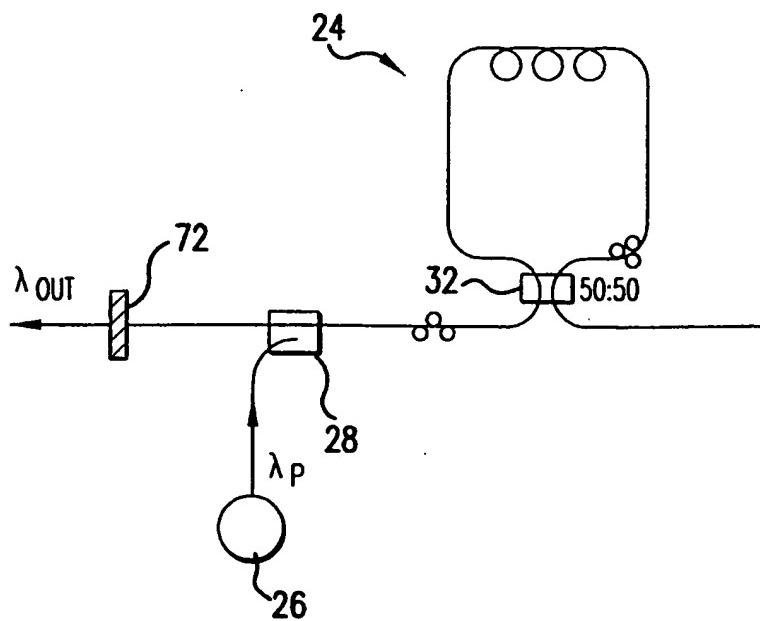


FIG.11

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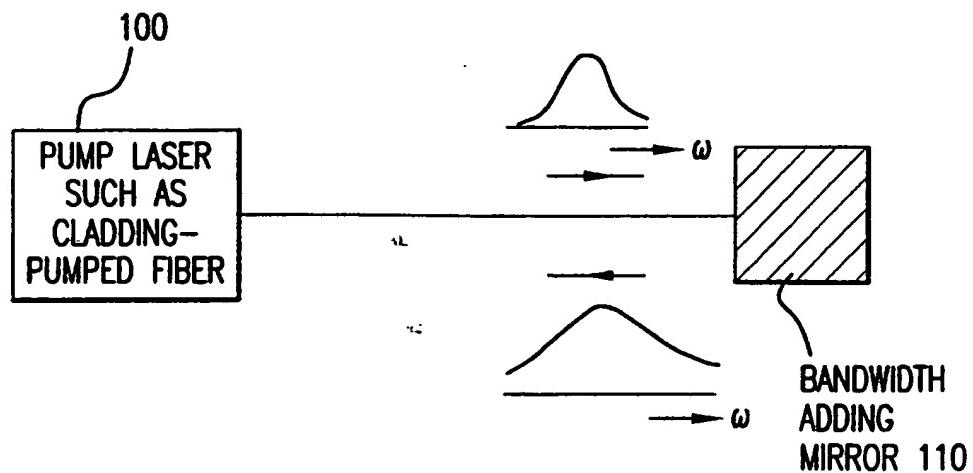


FIG.12

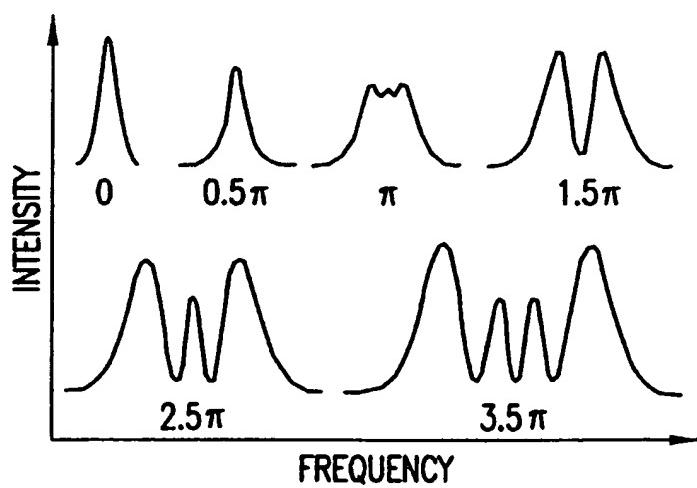


FIG.13

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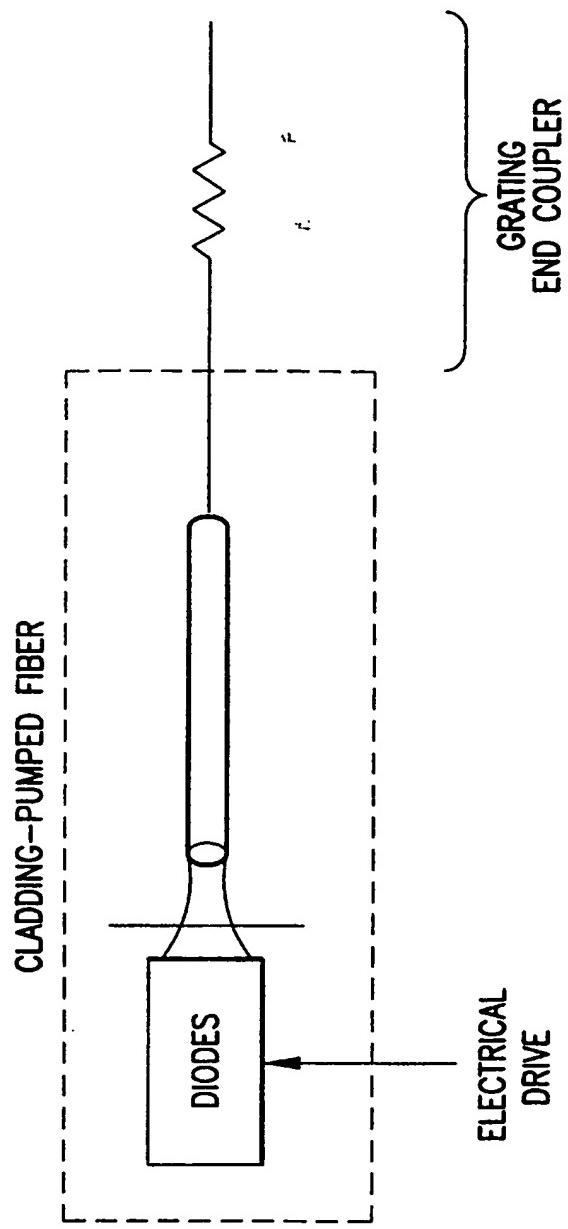
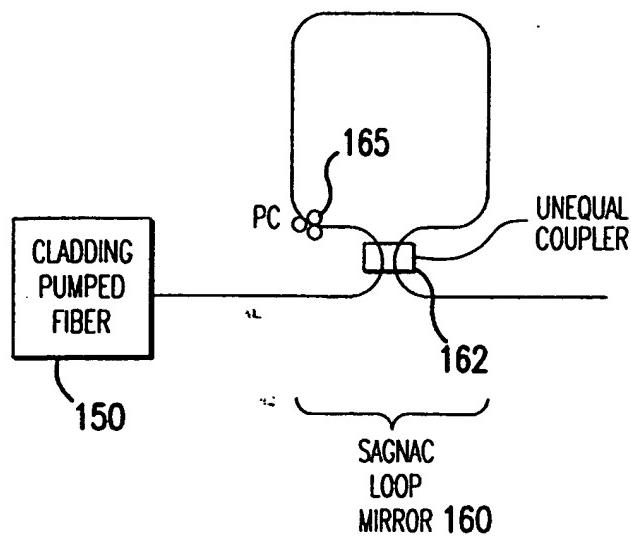
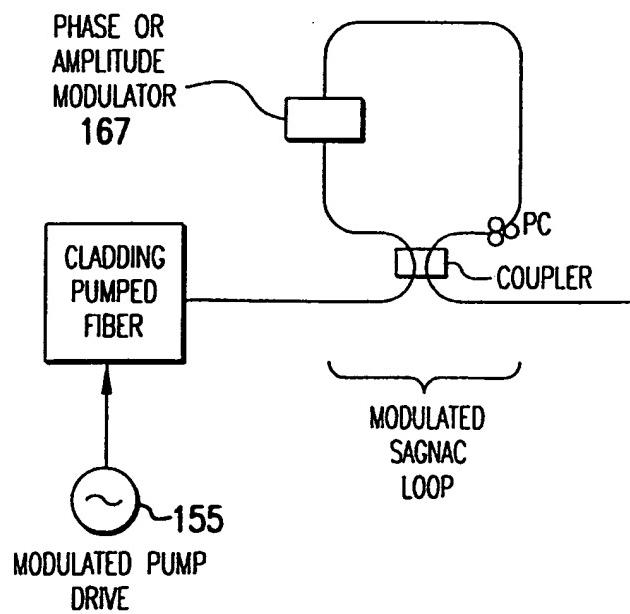


FIG. 14a  
PRIOR ART

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**FIG.14b**  
PRIOR ART



**FIG.14c**  
PRIOR ART

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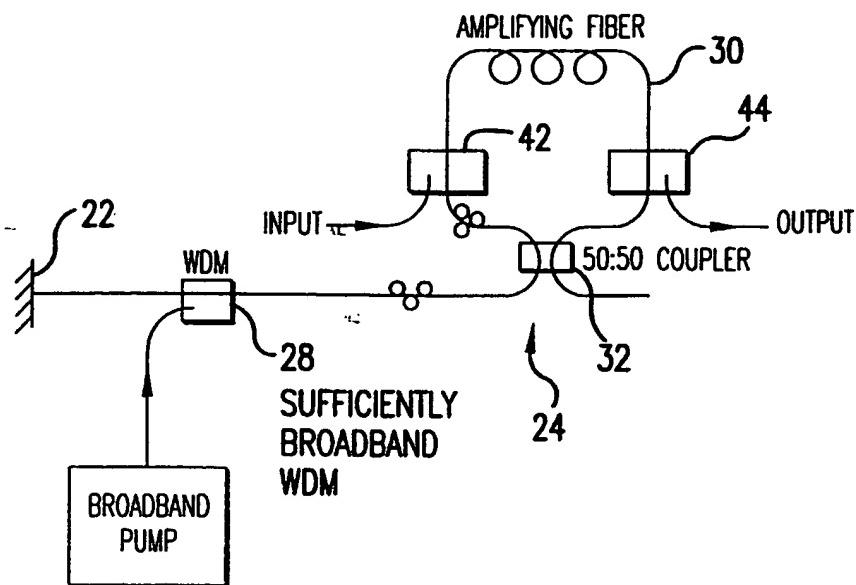


FIG.15a

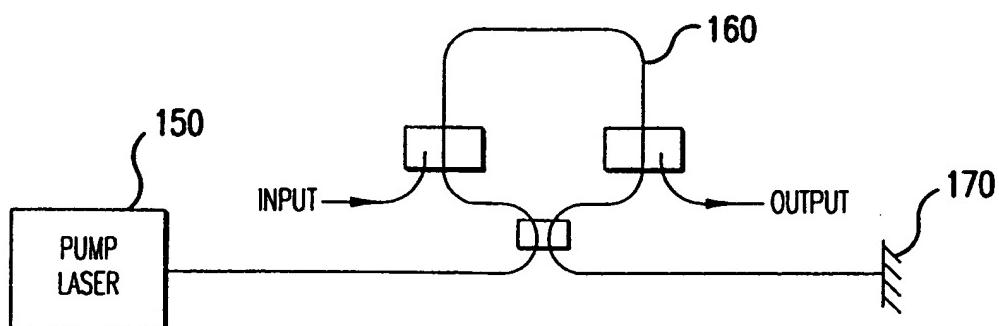


FIG.15b

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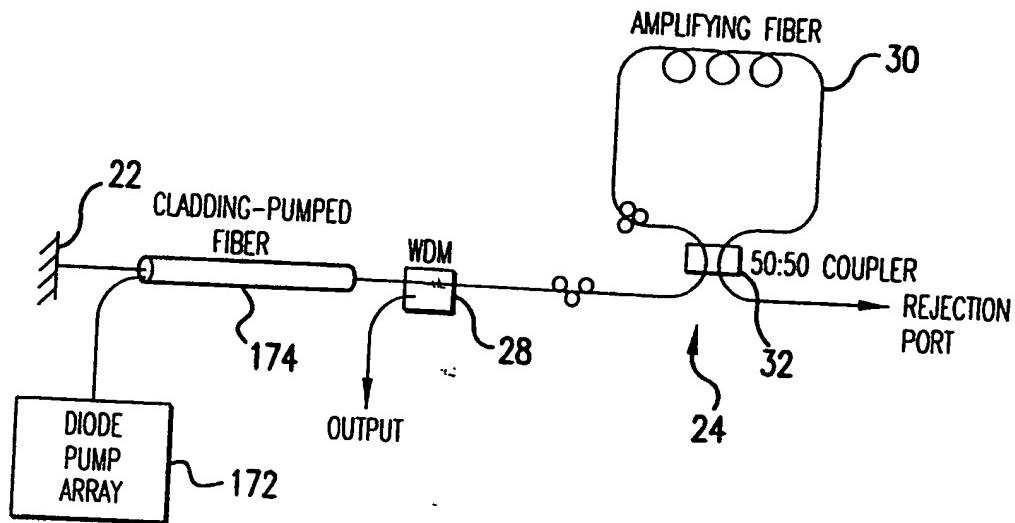


FIG.16a

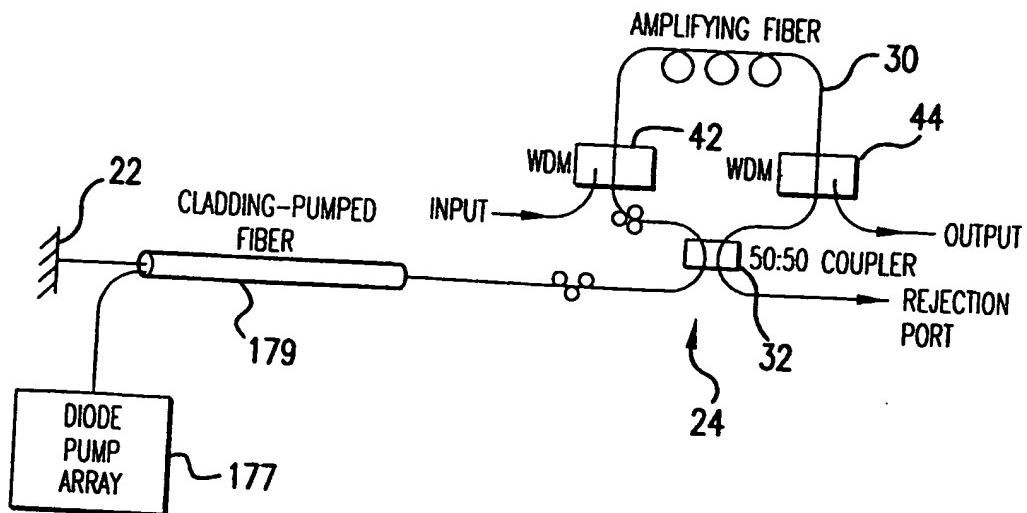


FIG.16b

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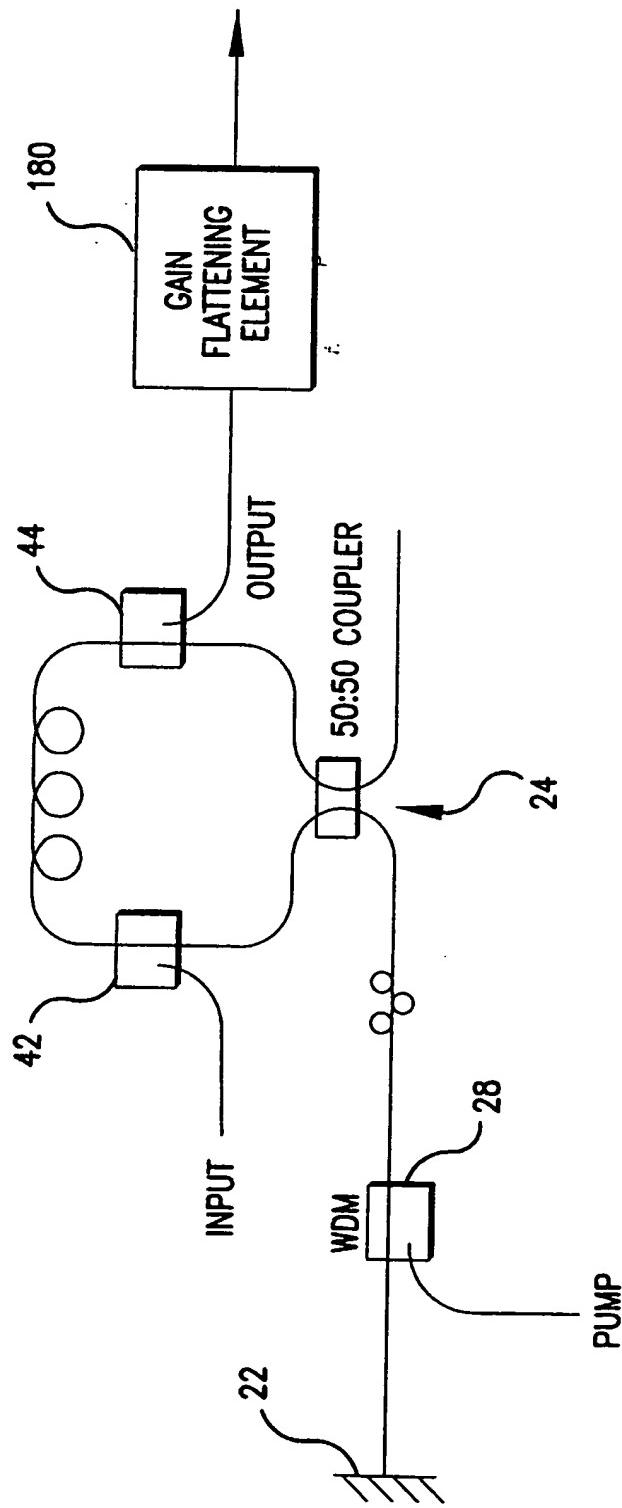


FIG.17

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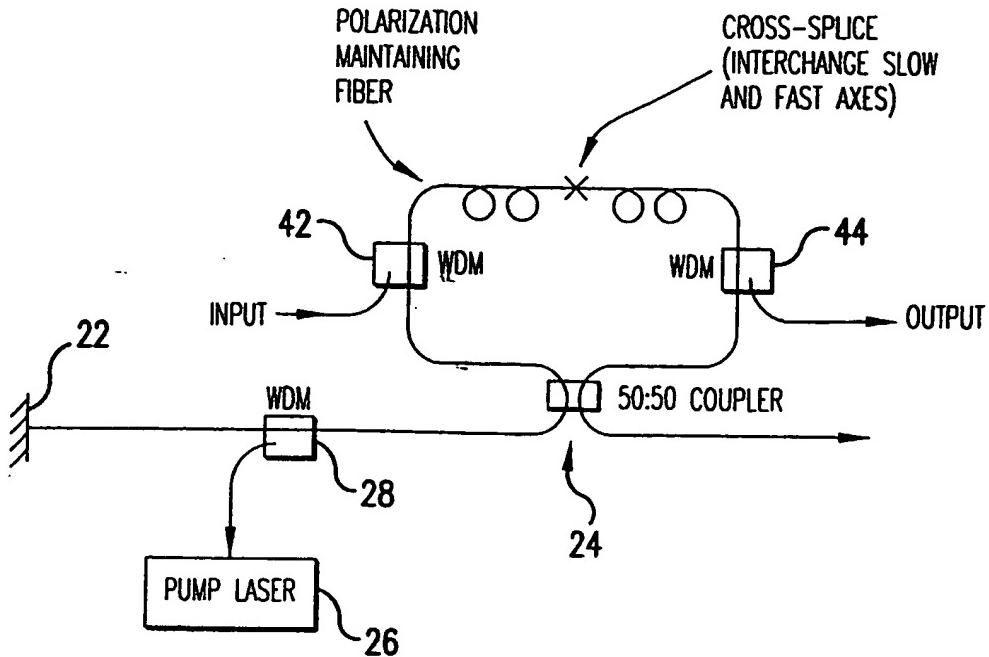


FIG.18a

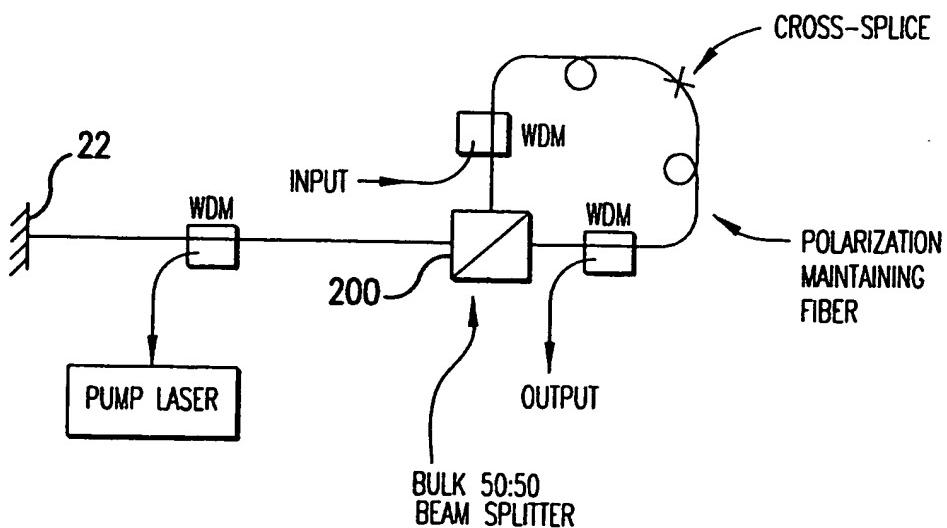


FIG.18b

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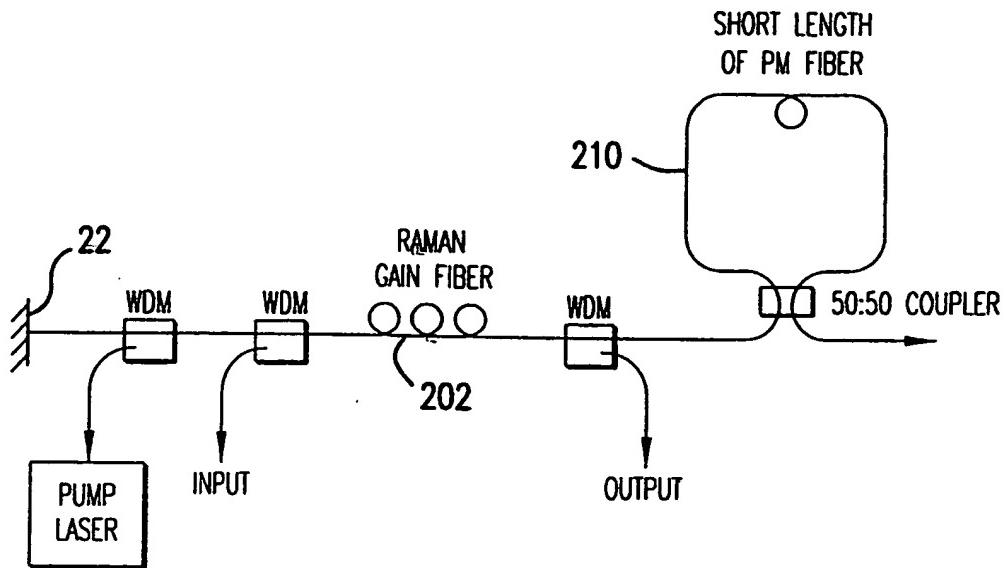


FIG.19a

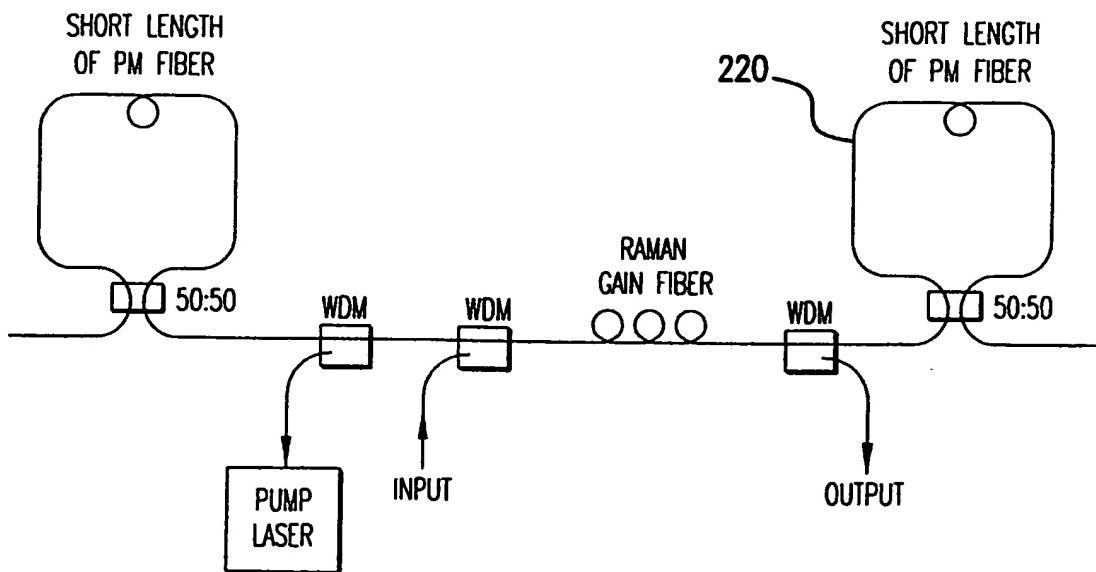


FIG.19b

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PCT/US99/07202

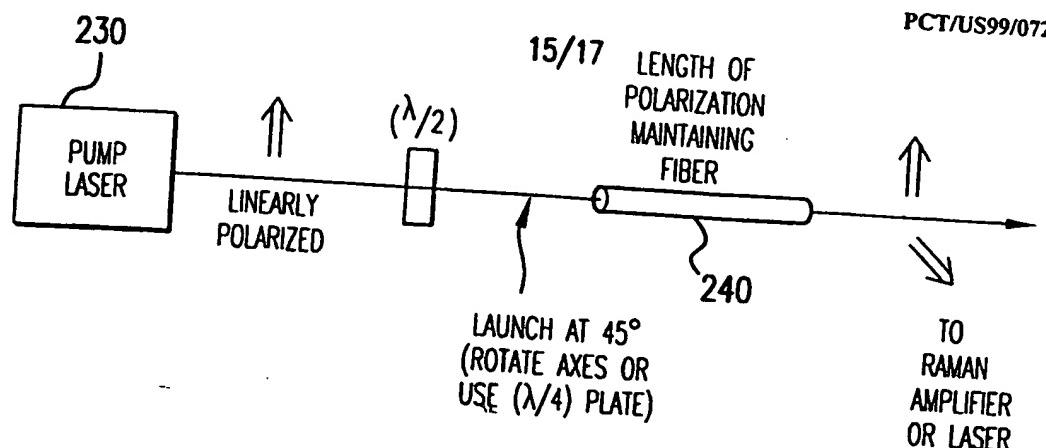


FIG. 20a

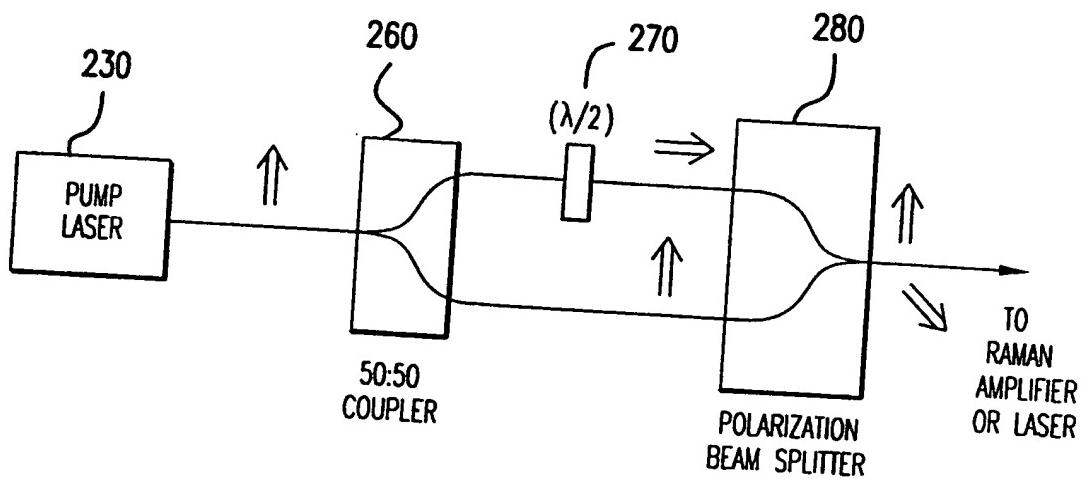


FIG. 20b

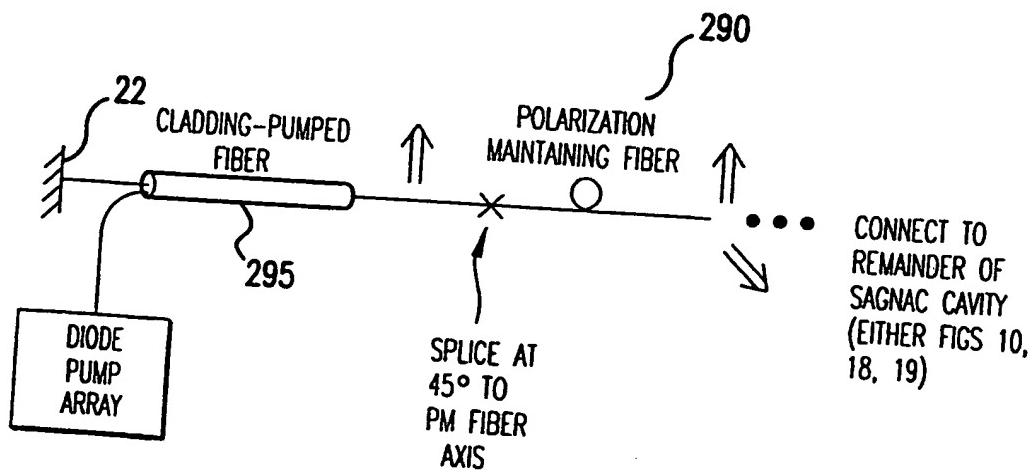


FIG. 21  
SUBSTITUTE SHEET (RULE 26)

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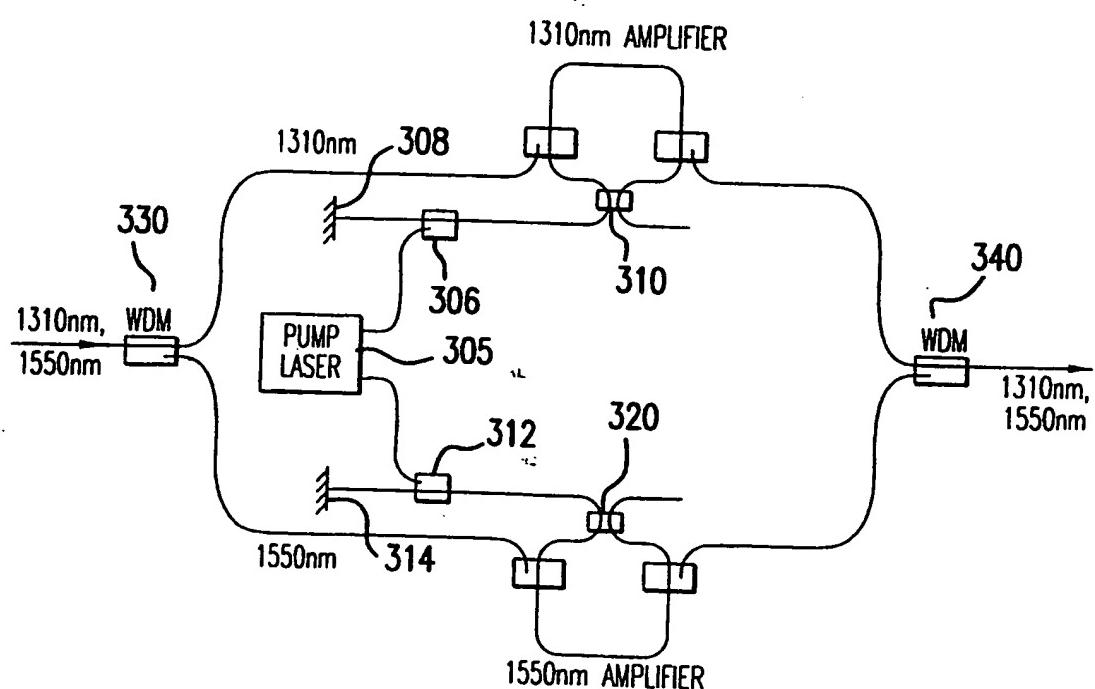


FIG.22a

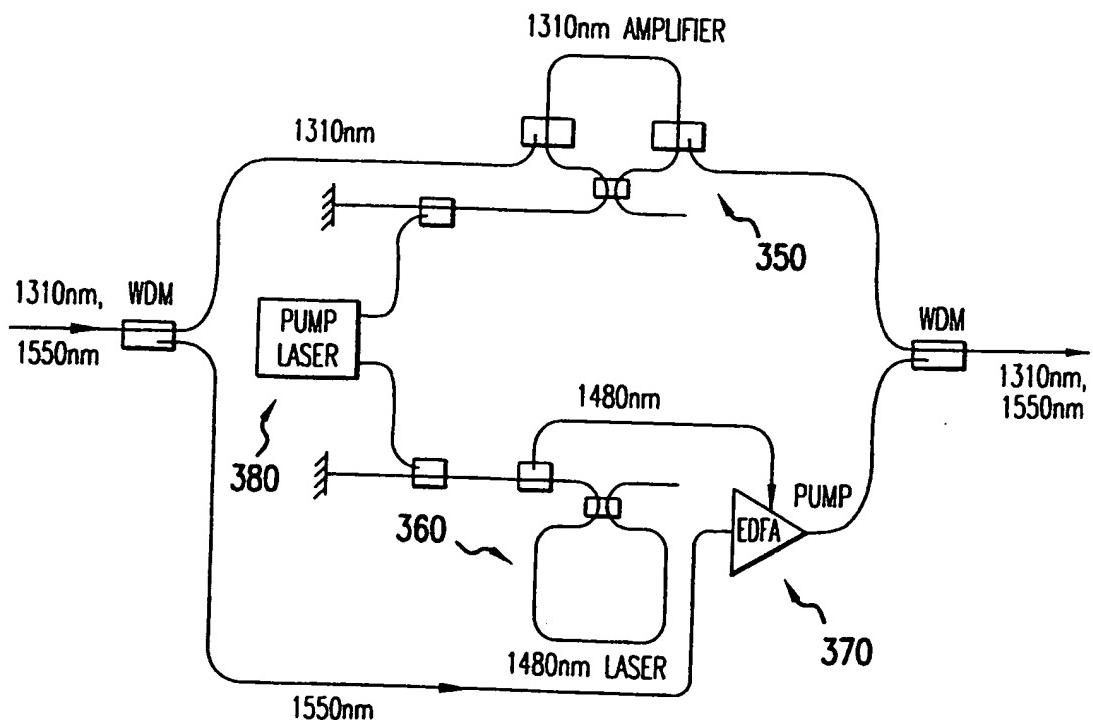


FIG.22b

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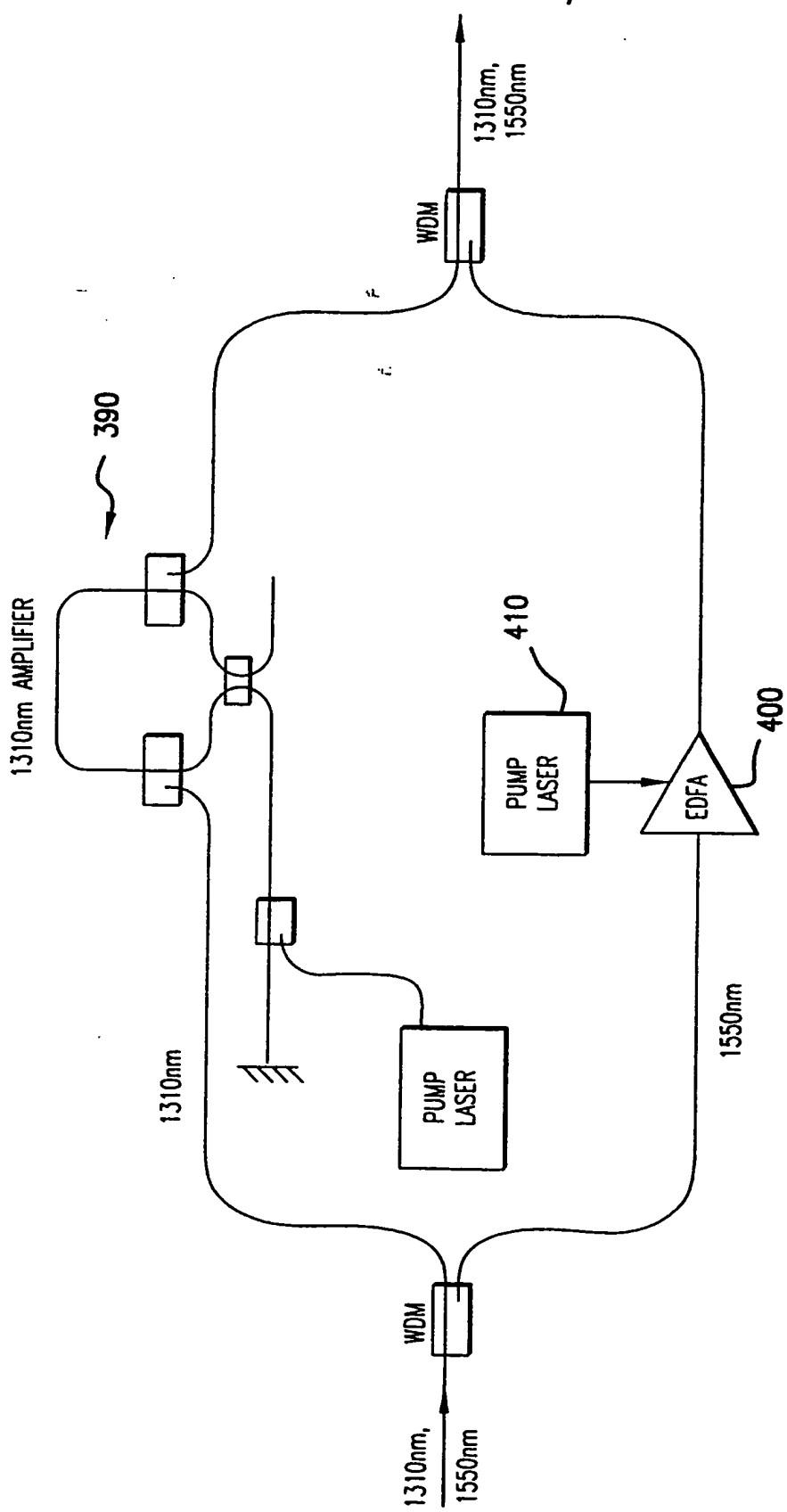


FIG.22c

## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US99/07202

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H01S 3/30

US CL :372/6

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 372/6, 21,22,27,28,39,92,94,96,97,99,106,3; 356/345; 359/115,127,133,134,333,341,345,346; 385/39,42,122,47

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

U.S. PTO APS search terms: sagnac?(2A)raman?(2A)amplif? and reflector? and loop?(2A)mirror? and pump?

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A,P	US 5,778,014 A (ISLAM) 07 JULY 1998 (07/07/98) NOTE ENTIRE DOCUMENT.	1-94
A	US 5,497,386 A (FONTANA) 05 MARCH 1996 (05/03/96) NOTE ENTIRE DOCUMENT.	1-94
A	US 5,673,280 A (GRUBB ET. AL.) 30 SEPTEMBER 1997 (30/09/97) NOTE ENTIRE DOCUMENT.	1-94
A	US 5,513,194 A (TAMURA ET. AL.) 30 APRIL 1996 (30/04/96) NOTE ENTIRE DOCUMENT.	1-94

Further documents are listed in the continuation of Box C.

See patent family annex.

* Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
*A* document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
*B* earlier document published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
*L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Z"	document member of the same patent family
*O* document referring to an oral disclosure, use, exhibition or other means		
*P* document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

19 JULY 1999

Date of mailing of the international search report

11 AUG 1999

Name and mailing address of the ISA/US  
Commissioner of Patents and Trademarks  
Box PCT  
Washington, D.C. 20231

Facsimile No. (703) 305-3230

Authorized officer

BRIAN HEALY



Telephone No. (703) 308-2693